Knittable electronic textiles for intelligent soft wearables

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Abstract: This review examines knittable electronic textiles as a foundational platform for soft wearable systems. Knitting's interlooped, three-dimensional architectures and computationally-enabled design allow the fabrication of customized electronic textiles that conform to the body while supporting integrated sensing, actuation, processing, communication, and power delivery. By constructing structures from fibers to full fabrics, knitted systems offer stretchability, breathability, and mechanical resilience, supporting functional garments and pathways toward intelligent soft wearable technologies.

Introduction

Textiles are among humanity's oldest technologies and are deeply embedded in culture, identity, and survival [1]. They mediate the relationship between the body and the world by providing protection, warmth, and shelter while also enabling expression, symbolism, and social meaning. This enduring dual role, as both bodily and environmental interface and cultural medium, continues today as technology becomes integrated directly into textile structures [2, 3].

Because fabrics are worn directly on the body and remain in continuous contact over long durations, they offer exceptional real estate for integrating systems that sense, respond to, and communicate information about the body and its environment. Textiles, particularly knitted architectures, naturally conform to complex anatomy, accommodate motion, and maintain comfort and breathability. Their loop-based structure also provides inherent mechanical compliance and structural programmability, making them well-suited for soft, flexible, and stretchable electronic systems and enabling functional yarns and electronic components to be integrated directly within the textile structure in ways that rigid or skin-mounted electronics often cannot achieve without compromising wearability or acceptance.

The roots of electronic textiles (e-textiles) extend well beyond the digital era. Metallic elements were incorporated into textiles as early as the early modern period, when gold and silver yarns were woven into tapestries, garments, and metallic organza for fashion and interior applications [4, 5]. Although primarily decorative or symbolic, these materials have already demonstrated the integration of functional, conductive properties into fabric structures. It was in the twentieth century that electrical functionality became more explicit. As noted by Hughes-Riley, Dias, and Cork, some of the earliest examples of e-textiles can be traced to illuminated costumes used in the ballet La Farandole in 1883, in which small electric lamps were integrated into garments for theatrical effect [6]. While primarily aesthetic, these illuminated textiles represent some of the first documented instances in which electrical components were embedded directly into clothing. Subsequent developments in the early twentieth century led to more utilitarian applications. Patents filed between 1910 and 1970 describe electrically heated gloves, socks, and blankets, marking some of the earliest uses of conductive fibers for functional purposes in everyday garments.

Across this long trajectory, textile manufacturing has repeatedly intersected with computation. The Jacquard loom, introduced in the early nineteenth century, encoded weaving patterns using punched cards, establishing one of the earliest links between textiles and programmable logic [7]. This principle of pattern control through discrete instructions directly influenced the development of early computing machines and, later, digital logic and transistors. While twentieth-century electronics largely evolved toward miniaturization and rigid substrates, recent advances in materials science, flexible electronics, and low-power computation now enable sensing, actuation, energy storage, and communication to be embedded back into textiles themselves [8, 9].

Current e-textiles span a wide range of fabrication approaches, from surface-based conductive coatings and printed traces to deeper structural integration through embroidery, braiding, weaving, knitting, and non-woven assembly [10]. Each approach offers distinct advantages: weaving provides high-dimensional stability and precise yarn placement suitable for dense and planar architectures [11], while non-woven and laminated structures enable scalable fabrication, isotropic mechanical behavior, and post-processing techniques such as thermal or chemical annealing to tune electrical and mechanical performance [12]. Embroidery enables localized placement of functional yarns but typically remains applied onto pre-existing substrates rather than being seamless with the intrinsic textile structure [3], while braiding excels at producing mechanically robust, one-dimensional or tubular architectures but does not readily scale to two-dimensional fabric surfaces [13].

Knitting, however, occupies a unique position within this landscape. Defined by interlooped yarn architectures, knitted structures inherently support stretchability, three-dimensional form, and local compliance [14]. Unlike cut-and-sew or layered assemblies, knitting constructs complex geometries directly from a continuous yarn, enabling spatial variation with minimal material waste, similar to additive manufacturing. Compared to other textile fabrication methods, weaving offers structural stability but generally provides less stretch, comfort, and breathability, while embroidery enables precise placement of functional traces on existing fabrics but typically as an add-on layer rather than a structurally integrated textile system [10, 3]. Printing or lamination enables electronic functionality but can introduce scalability and customization limitations and often adds thicker layers that reduce flexibility and become fragile under high strain [15]. Knitting, in contrast, provides intrinsic stretchability and allows functional yarns to be integrated directly within the textile structure, making it well suited for soft, flexible, and body-conforming electronic systems. Knitting also aligns well with digital fabrication and computational design workflows, enabling systematic exploration of structure–function relationships across scales and, for wearable applications, customization of functionalities across different joints and body regions. For these reasons, this review focuses specifically on knittable e-textiles (Fig. 1a). To position our work within the current literature, a comparison with existing reviews on broader e-textile technologies is provided in Tab. 1.

In this review, we define *knittable electronic textiles* as electronic functionalities that are integrated directly during the knitting process, including through the plating, intarsia, or inlay of conductive or functional yarns, so that the electronic behavior is intrinsic and integrated to the knitted textile itself. Approaches based on post-fabrication additions, including printing, coating, lamination, or attaching external electronic modules onto an already knitted substrate, are considered outside the primary scope of this review. Overall, this paper surveys the evolution of knitting from its historical and cultural origins to its role in contemporary e-textiles. It first examines knitted structures and architectures across scales, from fibers and yarns to fabric-level systems (Fig. 1b). It then reviews approaches for integrating sensing, actuation, computation, power delivery, and energy harvesting within knitted substrates, highlighting how these functions can be structurally embedded rather than externally attached. Finally, this review presents a vision for computationally designed knitted e-textiles, pointing toward intelligent soft wearable systems in which multiple electronic modalities are seamlessly integrated within a unified textile platform.

History of knitting technologies and yarn developments

As illustrated in Fig. 2, knitting originated as a handicraft approximately 3,000 years ago [16]. Hand knitting evolved from ancient techniques such as *nalbinding* [17] and *sprang* [18], which were practiced in early Middle Eastern and Egyptian cultures. *Nalbinding* uses a single needle and short lengths of yarn to create a dense, looped fabric that does not unravel, whereas *sprang* produces highly elastic textiles by twisting and interlacing vertical yarns under tension without using any needles. During this long period of hand knitting, hand-knitters relied on simple needles and natural yarns such as cotton, wool, and silk.

During the medieval and Renaissance periods, knitting became formalized as a skilled urban craft in Europe through the establishment of knitting guilds and organized training of apprentices and journeymen [19]. The shift to automation began with The Stocking Frame developed by William Lee (1589). As the first machine to automate hand-knitting, it produced stockings and fine flat fabrics, which were in high demand for fashion at the time. The Stocking Frame relied on a *bearded* needle—consists of a thin hook at the top and a straight shank (the needle's body). Unlike manual knitting, the bearded needle requires a separate mechanical part called a presser. After the yarn is placed on the hook, the presser bar pushes the flexible beard into a recess in the needle's stem. While this was a major leap in speed, the need for a presser bar made the machine's movement complex and limited its efficiency [16, 20].

By the 19th century, the invention of the *latch* needle (1847) transformed knitting by eliminating the need for a presser [16]. Unlike the bearded needle, the latch needle has a self-closing gate that opens and closes automatically as yarn moves, enabling circular machines that produced continuous tubes of fabric and supporting early mass production. In the 1880s, punch cards—adapted from weaving—introduced programmability by mechanically encoding which needles should operate, allowing automated multi-colored patterns and complex stitches such as lace. In 1953, electronic needle selection replaced punch cards with electrical signals and electromagnetic switches, establishing the foundation for modern computer-controlled knitting and digital fabrication.

In the late 20th century, computer control transformed knitting into a digital fabrication method, exemplified by Shima Seiki's WholeGarment technology. Unlike traditional knitting, which produces flat pieces that must be cut and sewn, WholeGarment enables seamless garments to be produced in a single continuous process using multi-needle bed systems and precise needle control. While a standard machine uses only two beds—front and back—to knit simple tubular structures, advanced 3D systems use a four-bed configuration. This multi-layered design enables more complex stitch transfers across beds, allowing different garment sections to be knitted and joined simultaneously. Building on such developments, recent research has explored solid knitting, which extends knitting beyond hollow shells to produce dense, volumetric structures through three-dimensional grids of interlocked stitches. [21].

With advancements in knitting machines, the 20th century also saw the rise of synthetic fibers such as nylon and polyester, which transformed the knitting industry [22]. These materials are more durable and elastic than natural fibers, making them well suited for sportswear and technical textiles while enabling control over properties such as stretch, moisture management, and thermal insulation [16, 23]. More recently, the development of conductive, shape-changing, and computing yarns [24, 25, 26, 9] has enabled electrical and mechanical functionality to be integrated into knitted structures through automated fabrication processes [27, 28], expanding knitting into applications such as wearable electronics and interactive textiles.

Knitting structure

Knitting is a hierarchical manufacturing process that creates fabric through an interlocking loop architecture. In this architecture, a new loop of yarn is pulled through a previous one to create a continuous chain of mechanically connected elements, also known as a *stitch*. These loop-over-loop structures expand horizontally along the *course* direction and vertically along the *wale* direction, collectively forming a fabric. This loop structure allows the fabric to stretch and bend easily as the loops change their shape and slide against each other. In addition to mechanical flexibility, this loop-based architecture renders the textile inherently programmable. By controlling the size, connectivity, and tension of the loops, textile characteristics, such as breathability, elasticity, and surface texture, can be precisely tuned across the fabric. Finally, the knitting process enables the seamless integration of various materials by switching from standard to functional yarns, such as conductive fibers, at any specific location. This enables the direct embedding of sensors and electronic circuits into the fabric structure, rather than attaching them later. Therefore, knitting offers a versatile platform for integrating mechanical design and electronic components into a seamless fabric structure [29].

As shown in Fig. 3, the knitting process involves a multi-scale system that scales from individual fibers to complete garments. The process begins with the yarn, forms individual stitches, and builds into 2D or 3D fabrics. At each level, properties such as stretch, thickness, and functionality can be precisely adjusted. This structured approach allows sensors and conductive materials to be integrated directly into the fabric. The following sections explain each part of this hierarchy in detail, from basic knit patterns to complex three-dimensional structures.

Fiber and yarn

The fiber and yarn serve as the fundamental elements that determine both the physical performance and functionality of the textile. The parameters such as color, texture, thickness (gauge), and inherent stretchability determine the final fabric's weight, tactile feel, and mechanical response [30]. In addition, the functionality of the yarn, such as its conductivity or resistance, determines the performance of the knittable e-textile. Silver-plated conductive yarns are widely used for knittable e-textiles because the plated yarns balance electrical performance with durability; these yarns can maintain stable conductivity even after approximately 50-100 wash cycles [31, 32]. Because the yarns are subjected to sharp bending and high friction during loop construction, such conductive and mechanically durable yarns are compatible with the knittable e-textiles [33]. Several other methods are used to create functional yarns suitable for knitting: (i) blending conductive staple fibers [34], such as stainless steel or carbon, with traditional textile fibers like cotton or polyester, (ii) core-spinning [35], where a functional filament is wrapped with a flexible fiber, and (iii) dip-coating or dyeing processes [36, 37] that apply conductive polymers or nanomaterials directly onto the yarn surface.

Stitch

At the stitch level, fibers and yarns are organized into specific stitch patterns that define the local geometry and mechanical behavior of the textile. A stitch is defined as the smallest unit of a knitted fabric, formed by a single loop of yarn interlocking with its neighbors. The "stitch" section of Fig. 3 is categorized into basic three types: basic, texture, and shaping knit [38, 39, 40, 41, 42, 43]. Basic knits, such as *plain (single jersey)* or *rib*, establish the fabric's fundamental stretch and density. *Plain* knit pulls all loops to the same side of the fabric, while *rib* knit alternates between face and reverse loops. This alternating structure creates a ridged texture, which makes the rib knit more stretchable than the plain knit. As a result, the plain knit is typically used for the garment's main body, while the rib knit is applied to the cuffs and collars to ensure a tight, comfortable fit. Texture knits control the yarn's path and the fabric's volume through *float (miss)* or *tuck*. *Float*, which passes the yarn across the fabric without forming a loop, is used to create a flat bridge across the fabric surface, whereas *tuck*, which holds multiple loops simultaneously, is used to add thickness and volume to the textile. As explained in the next section, these stitches are essential for techniques like intarsia and jacquard knit, allowing functional yarns to be hidden and routed invisibly behind the textile. Finally, shaping knit employs *increase* or *decrease* to vary the number of active stitches in a row. These stitches allow the fabric to widen or narrow, enabling the creation of complex shapes that follow the three-dimensional contours of the human body.

2D fabric

At the fabric level, individual stitches are organized into 2D fabrics to define the spatial layout and electrical networking of the textile [44]. As shown in the "2D fabric" section of Fig. 3, several techniques are used to integrate functional yarns into these layouts. *Intarsia* and *jacquard* knits are the main methods for creating functional patterns. While *intarsia* assigns separate yarns to specific, isolated regions, *jacquard* relies on the *float* or *tuck* knit to carry inactive yarns across the back of the fabric. *Intarsia* is typically used to place localized functional parts, such as a single sensor pad or an electrode. On the other hand, *jacquard* is used for (i) multi-layered routing; the *float* or *tuck* on the back side acts like hidden wires [45] and (ii) stitch-level control over the vertical stacking of yarns by switching which yarn is placed on the surface at each loop [46]. When a design requires a large-scale or stable multi-layered structure, *plating* knit is preferred because it maintains a consistent layered relationship throughout every stitch. While *jacquard* selectively swaps yarns in the narrow surface, *plating* holds two yarns in a fixed orientation—one strictly on the face and the other on the back—for the entire area. This creates a solid, multi-layered fabric, which is essential for making pockets or holders for electrical cords [47]. Furthermore, *plating* is utilized for functional separation through layering. By positioning a conductive yarn on the outer surface, a non-conductive yarn on the inner surface, *plating* can physically insulate conductive wirings against the human dielectric skin [48, 49, 50].

The other techniques include *interlock* and *inlay*. *interlock* knit provides a robust double-sided structure composed of two interlocking *rib* stitches. This structural stability provides a robust and flat foundation, making it an ideal substrate for mounting rigid electronic components or hardware connectors that require a reliable surface. *Inlay* knit incorporates yarns horizontally or vertically without forming loops. This unique method allows for the integration of materials that are typically too rigid to be knitted, such as thin copper wires, directly into the fabric. By crossing horizontal and vertical inlays, it can construct a matrix-like grid of conductive paths across the garment. This grid structure is highly effective for creating large-area sensing arrays [51], similar to the weaving approach.

3D fabric

Knitting is far more than a way to make flat fabric; it is a sophisticated method for building three-dimensional garments. By interlocking loops of yarn using two parallel rows of needles, modern machines can create complex shapes. By alternating stitches between these two rows, the machine can produce a continuous circle of fabric known as a *tubular* knit. This allows for the creation of entirely seamless garments, such as sleeves, socks, and gloves, which are formed as a single piece without the need for post-production sewing. Beyond simple tubes, the geometry of the textile can be precisely controlled to add specific curves and shapes. By adding extra rows of stitches in localized areas or adjusting the tightness of individual loops, the fabric can be made to dome, bend, or bulge [52]. This built-in shaping enables to replicate the intricate contours of the human body or create jointed structures that move naturally. For smart garments, this level of control is essential, as it ensures that sensors and electronic components maintain consistent, stable contact with the skin. Another powerful technique is *spacer* knit, which creates two separate fabric layers connected by internal yarns to form a cushioned, sandwich structure [53]. This inherent mechanical resilience enables it to function as a spring-like substrate for pressure sensors and mechanical energy harvesters, converting compression-recovery cycles into electrical signals or power. Furthermore, the internal architecture acts as a thermal barrier to maintain the temperature gradients required for thermoelectric harvesting. Together, these multi-dimensional capabilities transform knitting from a traditional craft into a sophisticated engineering platform. It enables the direct fabrication of functional, high-tech textiles that are perfectly adapted for both the human form and integrated electronics.

Garment

With a combined design space spanning fibers and yarns, stitches, and two- and three-dimensional fabric structures, knitting enables the fabrication of complete garments in which color, texture, and three-dimensional shaping are intrinsically integrated, supporting forms ranging from beanies and sweaters to shirts and gloves. As an example, a knitted glove requires complex, localized shaping operations, including the splitting and rejoining of finger parts, gradual narrowing in the palm region to achieve anatomical fit, and region-specific textures at the wrist to balance elasticity and stability. Color variation can be selectively introduced to encode functional regions, improve visual alignment during wear, or support design aesthetics without additional processing steps. Beyond structural and aesthetic control, the integration of functional materials further extends garment-level capabilities. Conductive, elastic, or responsive yarns can be spatially embedded via unique knitting structures to introduce electrical functionality within the garment architecture. Therefore, by coordinating yarn properties, stitch operations, fabric architectures, and 3D shaping strategies, knitted e-textiles can seamlessly integrate sensing, actuation, computation, and communication and powering functionality within garments that remain soft and flexible.

Functional modalities

With the knowledge of knitted loop topology and multiscale textile architectures, alongside advances in functional fibers and miniaturized integrated circuits, knitted e-textiles are evolving into substrates for complete electronic systems rather than carriers of discrete components. This design space encompasses multimodal sensing, including proxemic, tactile, strain, electrophysiological, and environmental modalities, as well as textile-native actuation through pneumatic, thermal, electroactive, and magnetic mechanisms. In parallel, computation is enabled through embedded chips and microfabrication, while power delivery is shifting from rigid battery packs toward fiber- and fabric-level storage and harvesting, including knittable batteries and supercapacitors, triboelectric and piezoelectric generators, and near-field power transfer via textile coils and body-coupled links.

Interconnects

Interconnects form the electrical pathways that allow signals and power to move through an electronic system, linking individual sensors, electrodes, and other functional elements to each other and to external circuitry. In knitted e-textiles, where sensing elements may be distributed over large, deformable surfaces, reliable interconnects are essential for maintaining signal integrity under stretch, bend, and compression [54, 55]. Because knitted structures naturally deform, an interconnect must exhibit low resistance and minimal resistance change under strain; otherwise, the interconnect itself becomes a sensor, corrupting the intended measurement. Therefore, an ideal interconnect requires low gauge factor (GF) and low resistance so that its electrical behavior remains stable regardless of mechanical deformation [56]. Additionally, depending on the intended application, conductive fibers or yarns must be selected not only for conductivity, but also for minimized crosstalk, washability, and durability [57], making interconnect design a foundational constraint in the construction of functional textile circuits.

At the stitch level, interconnects or electrodes emerge from the topology of conductive yarn loops, as they are essentially a complex network of series and parallel resistive, as illustrated in Fig. 4.a [58]. Each knitted loop can be modeled as a small resistor, and the fabric behaves as an integrated circuit whose electrical performance depends on loop-to-loop contact resistance and mechanical stress [59]. The electrical behavior of an interconnect is fundamentally tied to its geometric architecture. In weft knitting, the basic structural unit is the stitch, comprising a head, two legs, and two feet. Its geometry is well defined in classical models such as the ones by Leaf and Glaskin [60], and Munden [61]. The geometric loop model provides the foundational description of how knitted stitches derive their form and physical dimensions, defining the loop length l_M as a function of stitch width, height, and yarn thickness [62]. Zhang et al. [63] and Li et al. [64] extend this analysis into the electrical domain through resistive-network models that treat each knitted loop as a combination of length-related resistance and contact resistance. Their framework formalizes how stitch topology, wale–course configuration, and inter-fiber interactions govern electrical conduction across knitted architectures. Utilizing these resistive-network models, one can derive systematic analytical expressions for the equivalent resistance of conductive knitted structures spanning multiple courses and wales.

In addition to loop-to-loop direct current (DC) contact resistance models, the electrical behavior of textile interconnects can become frequency dependent. At higher operating frequencies, conductive textile pathways exhibit parasitic capacitance and inductance arising from yarn geometry, inter-yarn spacing, and the dielectric properties of textile substrates. These parasitic effects influence signal propagation, impedance matching, and electromagnetic coupling between neighboring conductive traces. For example, textile transmission lines fabricated from conductive yarns exhibit measurable impedance variation and signal attenuation across radio-frequency ranges due to distributed resistance and contact interfaces within textile structures [65]. Similarly, textile antennas integrated into garments demonstrate frequency-dependent impedance behavior and radiation performance that are sensitive to fabric geometry and mechanical deformation [66]. Understanding these frequency-dependent characteristics is therefore essential when knitted interconnects are used for high-speed and high-frequency communication or antenna integration in wearable systems.

Stitch pattern selection directly governs interconnect performance. For example, linen stitch was identified as an optimal single-bed interconnect pattern due to its low GF and relatively low baseline resistance, while full cardigan stitch performs best on a double bed [56]. Additionally, interconnection direction in the knit, wale-wise (WW) (Fig. 4.b) and course-wise (CW) (Fig. 4.c), can further fine-tune sensor performance. When looking at WW and CW conductive knit-and-miss structures, it was found that CW patterns maximize conductive contact points and achieve extremely low initial resistance (0.28–0.44 Ω) with negligible change even at 2× strain [54]. Beyond stitch design, material choices, such as fiber coatings, inherently conductive yarns, or filled filaments, also influence structural behavior, impacting overall conductivity, mechanical range, and textile manufacturability.

Scaling up from the loop level to the structural level, knitted interconnects can be integrated as embedded pathways, multi-layer conduits, or vertical and horizontal routing systems. This concept has been extended through a fully knitted wearable where sensors, resistors, and interconnects were all fabricated within a single continuous knit (Fig. 4.d), enabling high stretchability (>140% for interconnects) [54]. Such structural strategies allow e-textiles to function as integrated circuit boards in fabric form, where electrical routing is embedded within the textile architecture itself.

To mitigate electromagnetic interference and signal coupling between conductive yarns and interconnects, shielding and grounding strategies may also be incorporated into textile architectures. Multi-layer conductive knit can act as electromagnetic shields that reduce noise pickup and cross-talk between signal lines [65, 67]. It can also stabilize signal transmission by providing a reference potential and reducing electromagnetic radiation from signal-carrying interconnects [68]. Finally, another important consideration for textile interconnect systems is the interface between soft knitted conductors and rigid electronic components. Reliable electrical connections between textile circuits and conventional electronics are typically achieved through connectors, conductive snaps and pads, solderable interposers, or flexible printed circuit bridges [69, 70]. For example, conductive snaps and detachable connectors are commonly used in wearable garments to enable removable electronics while maintaining washability [71]. Embroidered or sewn-in conductive wires or yarns can provide solderable or pressure-contact interfaces that connect to printed circuit boards [72]. In addition, pocket-based or mechanically clamped contacts can create electrical connections through compressive pressure between textile interconnects and electronic modules [73]. Flexible printed circuits (FPC) are also widely used to interface textile interconnects with integrated circuits while accommodating mechanical mismatch between soft fabrics and rigid electronics [74].

Knitted interconnects are used anywhere from signal routing, communications, to power delivery (e.g., knittable I^2C data and power routing by Li et al. [48]). More generally, interconnects are used to link antennas, heaters, electrodes, and flexible circuits throughout smart garments, where they must withstand repeated cycling, washing, and large deformation without degrading. Their role is not only to connect components, but to do so in a way that preserves the textile's softness, stretch, and wearability, in turn making interconnect design critical in knitted electronics.

Sensing

Knitted textiles have emerged as a versatile platform for multimodal sensing, enabling mechanisms such as capacitive, piezoresistive, piezoelectric, and triboelectric transduction to detect a wide range of stimuli, including touch, pressure, strain, deformation, proximity, and environmental or chemical cues. This breadth of functionality is enabled by the intrinsic properties of knitted fabrics. Their looped, three-dimensional geometry provides tunable compressibility, elasticity, and porosity, while the flexibility of the knitting process allows seamless integration of functionalized yarns. Through careful material selection and the design of multilayer knitted architectures, fully textile-based sensing systems can be realized and integrated into everyday wear.

Touch and proximity

The use of conductive yarns and knitting techniques enables the development of interactive fabrics that detect and respond to human touch or presence. Touch sensing can operate through several approaches, such as through capacitive [75], resistive [76, 77], magnetic [78], or triboelectric [79, 80] sensing. Prior work conducted on touch sensing is summarized with Table 2. Touch sensing in knitted fabrics can be achieved by creating a double-layered sensing structure with a layer of shorter conductive yarn rows under another layer of conductive yarn [81]. These two layers, when subjected to pressure, cause a decrease in resistance as the conductive yarns make contact, allowing the fabric to sense touch [82]. The ability to measure these changes in resistance and capacitance allows for highly responsive and flexible sensing interfaces directly integrated into knitted materials. One example of this can be seen in Vallett et al.'s array of capacitive touch sensors, connected via one continuous carbon fiber trace with only two electrodes. Based on the rise time of these two electrodes, a model was created to output where the user touched the sensor array, decoupling touch location and capacitance. When comparing the user data to the model, they determined that the sensor array was able to detect coarse touch locations [83]. Similarly, a tactile sensor made from two knitted fabrics, the bottom with conductive yarn traces and the top with contact area can be turned into a game controller (Fig. 4.e-f). Each 28 by 28 stitch sensing unit was characterized, and the data showed that the continuous resistance drops from 190 to 25 kΩ as pressure increases from 0 to 17.5 kPa (Fig. 4.g) [84].

In addition to detecting touch, proximity sensing can also be integrated into knitted textiles to respond to the approach of a hand or finger. Proximity can be measured through capacitive sensing, where the knitted conductive structure functions as an electrode whose electric field is perturbed by nearby objects [85, 45]. In single-electrode capacitive sensing, the system measures changes in the electrode's self-capacitance: as a hand approaches, the effective capacitance increases due to the user's body acting as a weakly grounded capacitor. In active capacitive sensing, an additional driven or reference electrode is used to create a controlled electric field; changes in the mutual capacitance between the electrodes reveal the position or motion of nearby conductive objects.

Permanent magnets and ferromagnetic yarns can be embedded into knitted structures to enable both passive haptic feedback and binary sensing of presence [86] (Fig. 4.h). By utilizing knitting techniques such as splitting (extending a second sheet from a base sheet to create pockets or separate fabric sections) and plating (where one yarn is knitted on the front of a fabric, while the other is knitted on the back), pockets can be created for magnet placement and ferromagnetic patches can be seamlessly integrated (Fig. 4.i). These knitted ferromagnetic patches are able to interact with permanent magnets to produce measurable attractive forces (Fig. 4.j). Patterns with higher ferromagnetic-yarn density show steeper force–distance curves, enabling tunable haptic sensations on garments (e.g., wristbands, hats, gloves). Flipping-knit elements were used for sensing; when a magnet-carrying knit flips into contact with a ferromagnetic patch, a conductive path forms and resistance drops sharply, creating a clear binary signal. This expands knitted input modalities beyond analog pressure to include reliable state-change detection [86].

Touch sensing can also generate voltage through triboelectric means. By fabricating a conductive chenille yarn with acrylic fibers and a silver-plated nylon fiber, Dong et al. are able to create a triboelectric carpet [79]. The fibers were incorporated as an inlay through weft knitting with an elastic nylon yarn in a 1x1 rib structure. The chenille surface functions as the triboelectric layer, and under contact and separation, electron transfer can occur and charge can be generated. Sensor output depends strongly on the contacting material, force, and frequency, reaching approximately 39 V and 375 nA under 200 N and 3 Hz when tested against PE fabric. Under this load and frequency, the fabric demonstrated a maximum power density of about 2942 μ W/m^2 at 100 MΩ load resistance, and can even power small electronic devices such as a calculator. These various approaches demonstrate how knitting can unify diverse physical sensing principles into soft, seamless, and highly adaptable touch interfaces for interactive textiles.

Strain

Strain sensing in knitted e-textiles arises from the way mechanical deformation alters electrical pathways within engineered yarns and looped fabric structures. Under strain, resistance changes may occur due to shifts in conductive coating percolation, fiber–fiber contact dynamics, or deformation of the knitted geometry as it transitions between 2D and 3D configurations [87]. Many approaches have been explored, as the combination of yarn material properties and knitted structures ultimately dictates the sensing modality, namely piezoresistive, capacitive, triboelectric, or piezoelectric responses, each with distinct advantages, limitations, and application domains [88]. Piezoresistive and capacitive sensors are well suited for capturing continuous, dynamic motion with higher resolution [89, 90]. In contrast, piezoelectric and triboelectric sensors primarily detect transient or dynamic changes rather than static ones, but offer higher sensitivity to stimuli and the added benefits of self-powered operation and energy harvesting [91, 92, 93] Prior work conducted on strain sensing is summarized with Table 2.

In knitted e-textiles, piezoresistive strain sensing arises from how mechanical deformation modifies the electrical properties of conductive fibers or coatings. When a textile is stretched, compressed, or bent, changes in electrical resistance may originate from two mechanisms: 1) geometric effects, where deformation alters the length (L) and cross-sectional area (A) of the conductive pathway, and 2) intrinsic material effects, where the resistivity (ρ) of the conductive coating or composite changes under strain due to microstructure rearrangements, tunneling pathways, or percolation behavior. These relationships are captured by the general expression for resistance:

$$R = \frac{\rho L}{A} \tag{1}$$

As an example, Eom et al. demonstrate conductive coating such as PEDOT on a polyester fiber via polymerization and coating with Poly(methyl methacrylate) PMMA to create an insulated, conductive fiber [94] that can sense up to 20% strain with a decreased resistance during stretching (GF$\sim$ -0.76). Under large deformations, crack formations can occur on the sensing layer, leading to an increase in resistance, which can be harnessed for strain sensing [87]. Another study compares two knitted piezoresistive fabrics (KPFs) made by integrating elastic yarns with conductive yarns on a circular knitting machine. T-KPF (textured KPF) is made by randomly tangling conductive yarns to create interlaced zones in order to improve its mechanical properties and allow for better processing during knitting. parallel KPF (P-KPF) is made with the same number of conductive yarns, but maintains an ordered, parallel structure between all yarns. It is found that P-KPFs have lower resistance values (44kΩ) than T-KPFs (197kΩ) at rest. They also determine that P-KPF has more stable sensitivity during stretch and recovery and close to no hysteresis than T-KPF which has 25.72% hysteresis with 16% elongation [95]. Xing et al. developed a graphene (GR)/thermoplastic polyurethane (TPU) fibrous yarn, produced by a one-step electrospinning process, in which graphene nanosheets form a 3D conductive network inside the elastomeric yarn. When stretched, the conductive network changes to enable a large strain range (140%), a high sensitivity (GF = 46.19), and stable performance over 10,000+ stretch–release cycles [96].

Alternatively, fibers doped with conductive particles can show a resistivity change due to intrinsic molecular percolation under stress. Therefore, the resistance of these fibers can be modeled as a function of applied pressure through percolation theory [97]. One study prepared composite threads composed of polymer foam embedded with conductive particles of Bi_2Te_3. They posit that the volume fraction of a conductor in an insulating matrix will determine the conductivity of the composite system. Under a compressive volume change, the conductivity will be affected. They relate the pressure to the elasticity for a 1D fiber as follows:

$$P = E\frac{\Delta h}{h_0} \tag{2}$$

where P the applied pressure, E the Young's modulus of the composite, Δh the change in length, and h_0 the original length. After considering changes in volume due to Poisson's ratio for 3D volumes, they arrived at a resistance and pressure relation as follows:

$$\Delta logR = -s\Delta logP, \tag{3}$$

where R the resistivity and s the conductivity. It can be seen that a higher pressure and compression will result in a lower resistance. Likewise, as the fiber is stretched, the resistance will increase. These works demonstrate that the molecular properties of yarns can be tuned to affect the resistive properties of strain sensors.

As these yarns are knitted, the sensing efficacy can be further altered via knitted structures, such as stitch types. This is due to how stitches can affect the contact amount, in terms of length and pressure [98]. According to Holm's contact theory, the resistance between two conductive materials is dependent on their contact pressure and number of contact points [99], and can be defined as follows:

$$R_c = \frac{\rho}{2}\sqrt{\frac{\pi H}{np}} \tag{4}$$

where R_c contact resistance, ρ electrical resistivity, H material hardness, n number of contact points, and p contact pressure. Based on the equation, it can be seen that if all material constants remain constant, a higher contact pressure and increased contact area will reduce the contact resistance. Several studies have analyzed the sensitivity of knit conductive textiles in different stretching directions. It has been observed that silver-plated knit textiles stretched in the course direction tend to be more sensitive than those stretched in the wale direction, often showing a GF performance that is 2 to 8 times higher

[100]. GF is given by the equation:

$$\text{GF} = \frac{\Delta R/R}{\Delta L/L} \tag{5}$$

where ΔR the change in resistance, R the initial resistance, ΔL the change in length, and L the initial length. This equation highlights how more substantial resistance changes in the course direction lead to higher GF values, making textiles stretched in this direction more responsive to strain [100, 101]. Additionally, stitch types, such as rib, will also affect the strain sensitivity. One study found that rib stitches demonstrated a higher sensitivity with a GF of 3 to 18, compared to knit stitches with a GF of 3 to 11 [102].

Furthermore, manufacturing parameters, such as conductive yarn tension, stitch type and direction, and yarn property, will influence GF, working range, initial linearity of working range, and hysteresis. With that in mind, one knitted sensor was developed with a yarn that combined carbon fibers, an aluminum-coated yarn, and normal yarns. Under a 43% strain, the contact area between the aluminum-coated yarn and carbon fibers increases, thus decreasing the contact resistance, resulting in a resistance change of more than 10 times larger than in the unstretched state [103]. Understanding these parameters can aid in developing larger knitted architectures for wearable applications. For example, one work developed a sign language translation glove, based on knitted strain sensors [104]. Using a plain-plated knit structure with conductive yarn on the back, the sensor had a GF of 88, a response time of less than 0.1 s at 50 cycles per minute. By detecting and responding to finger joint bending movements, it was successfully able to recognize 12 Korean Sign Language gestures with an accuracy of 98.67%. Additionally, it has been demonstrated that wale-wise rib 1×1 and interlock ×2 stitches will produce a high GF (1.36 and 1.79, respectively) and large working ranges (21.70 pp and 40.44 pp, respectively) due to their stable yet highly extensible loop architectures. This makes them adequate stitch types for strain sensors [56]. These principles have been implemented into a strain sensing knee brace (Fig. 4.d) [105] that measured voltage changes during a walking gait cycle. Over two sessions where study participants walked at a speed of 1.5 km/hr for ten seconds, the knee brace was able to track voltage changes in real time with a standard deviation of 0.39 V and 0.41 V, respectively. The consistency between the two sessions demonstrates the adequate sensitivity of the sensor.

At the structural level, innovative fabric architectures can be exploited to create piezoresistive responses. For example, conductive pleats that overlap when laid flat, but shear away from each other when stretched will experience a linear increase in resistance due to a decrease in contact surface area. One such work fabricated this structure with an elastic fabric made from spandex yarn, and structure experienced an increase of resistance from 58 Ω to 127 Ω across a 14 mm stretch [76]. From these applications, it is apparent that knitted pressure and stretch sensors can be integrated from a fiber, stitch, or structural level to create complex sensors capable of stable, high-resolution pressure mapping for a multitude of applications.

Another approach to textile strain sensing beyond resistive methods is capacitive sensing. Capacitive sensors operate by measuring changes in capacitance as a material undergoes deformation, which affects the dielectric layer's thickness and the area of overlap between electrodes. In this setup, two layers of conductive knit fabric serve as electrodes, with a deformable dielectric material in between. The capacitance C of the sensor can be expressed by:

$$C = \frac{\varepsilon A}{d} \tag{6}$$

where ε is the permittivity of the dielectric material, A is the area of overlap between the two electrodes, and d is the thickness of the dielectric layer. As the textile stretches, the dielectric layer compresses, reducing d, while also potentially changing A due to the stretching fabric, resulting in a detectable change in capacitance. The change in area A is influenced by the Poisson effect, where the material tends to contract in the perpendicular direction when stretched in one direction. In knitted textiles, this effect results in dimensional changes not only in the thickness of the dielectric but also in the width of the conductive layers, further enhancing the sensitivity of the capacitive sensor.

Atalay et al. has demonstrated promising results in capacitive sensors that use conductive knit fabrics as electrodes with a silicone elastomer serving as the dielectric [106] (Fig. 4.k) The knitted fabric collapses the micropores of the dielectric under pressure (Fig. 4.l), and higher pressures from 25 kPa to 100 kPa increase capacitance from 0.6 to 1.6 $\Delta C/C_0$ (Fig. 4.m). Additional studies explored interdigitated multi-layer structures of conductive and dielectric layers, which improved the sensors' efficacy [89, 107]. These efforts, enabled by batch manufacturing and laser cutting techniques, allow for the production of large, customizable textile-based strain sensors.

Another approach leverages the piezoelectric effect with polyvinylidene fluoride (PVDF) film. One work looked at connecting the film to conductive yarns, then encapsulating the structure with non-functional textile yarns and resin [91]. This work leverages PVDF's strain sensing capabilities in order to measure the heart rate and respiration rate of human subjects under static and dynamic strain conditions. Under a static condition, such as sitting, the sensor was able to detect a 1.47 Hz heartbeat rate and a 0.2 Hz respiration rate. While walking, the respiration signal was lost due to motion artifacts, but the sensor was still able to attain a heart rate.

In parallel, extensive efforts have explored the development of nanostructured piezoelectric fibers, typically via electrospinning [108, 109, 110] or melt spinning [111, 112]. Bu et al.'s electrospun yarns were integrated into knitted patches for joint cuffs. These cuffs were able to detect joint bending angles due to induced strain. For example, a 30° knee flexion generated 0.905 V, while a 90° flexion generated 1.871 V [110].

Tactile pressure

Pressure sensing can be understood as strain sensing dominated by out-of-plane compressive strain. Resistive pressure sensors exploit compression-induced changes in contact resistance either at a fiber to fiber interaction level or stitch or fabric structural level. Varying composite materials structurally will impact resistivity. Prior works conducted on pressure sensing is summarized with Table 3. One work looked at how the positioning of conductive and polyester yarns in a plain knit in a 1 x 1, 1 x 2, or hybrid structure would affect the resistance and stability of the sensor. They found that adding the polyester yarn between rows of conductive yarn interferes with the successive conductive loops, thereby increasing the resistance. The hybrid yarn, a combination of conductive and polyester, maintained high structural stability with less resistance [101]. Intrinsic piezoresistive fibers can be fabricated by coating stainless steel fibers with a piezoresistive nanocomposite, then inlayed into knitted garments [51]. As two fibers are pressed together, the resistance drops from 8 kΩ to 2 kΩ. The sensing performance of these piezoresistive fiber pairs has been shown to depend strongly on stitch type and orientation within the knit structure [113] (Fig. 4n). In one implementation, two sensor elements were arranged with a tuck, knit, and front-miss stitch (Fig. 4.o), enabling the system to sense surface pressure.

At a structural level, pressure sensors can be made by having a compressive, resistive filler material between two conductive traces (Fig. 4.p-q), encased with non-conductive yarns. By applying different stitches such as knit, tuck, float, plying, and plating, while varying parameters such as filler spacing and density, the resistance and pressure saturation can be tuned [114]. This study found that sensor resistance drops by $\sim 90\%$ when actuated with moderate finger pressure of 2 N, with a strong alignment between applied force and conductivity readings (Fig. 4.r). Multiple sensors can be knitted together to create multi-cell sensor systems (Fig. 4.s). Fabric architecture, such as sandwiching piezoresistive fabric between conductive knits, can also be leveraged for pressure sensing. For example, pressure sensor arrays for sensing mats (45 x 45 cm with 256 sensors) and shoes (96 sensors) [55] can be used during exercise and gaming activities.

Knitted capacitive pressure sensors rely on the compressibility and multilayer geometry of knitted textiles to form soft, wearable capacitors whose capacitance changes under load.

In these systems, conductive layers, functioning as electrodes, sandwich knitted or engineered dielectrics in between. These spacers maintain separation between the electrodes, and subsequently, capacitance changes under applied pressure.

On a fiber level, the yarn thickness of the spacer is the dominating parameter that determines the capacitance of knitted pressure sensors. One work created 3D weft-knitted textile capacitors using conductive silver-coated nylon, insulating yarns, and PVDF-based spacer monofilaments. Measurements from these structures showed that overall thickness and electrode area dominated capacitance behavior, while spacer composition and plating had relatively minor impact; samples of equal thickness produced similar capacitance regardless of yarn chemistry [58]. In a similar experiment, samples of five-layer weft-knit spacer sensors were created, and it was found that a thinner diameter spacer monofilament (0.08 mm polyamide) produced greater sensitivity, with capacitance rising from 1.9 pF to 5.2 pF under compression [115]. These thinner-spacer sensors also saturated earlier, showing that sensing range and sensitivity can be tuned by changing the yarn thickness and spacer material. Additionally, with these sensors, resistance remained low (11–118 Ω), and they were effectively integrated into soft, interactive objects such as a teddy bear paw stress soother, a steering wheel for biometric information and abnormality detection, and a shoe insert for exercise.

Knitted spacer structures have been shown to enable a tactile pressure sensor. For example, as a flat-knitted elastic spacer fabric whose compressible knit core acts as the dielectric layer [116]. These knitted sensors demonstrated strong compression recovery and frequency-independent stability: Δ C/C_0 remained consistent across tested frequencies, and response times were under 150 ms at 30% compression. Another example work is conductive fabric electrodes with a thin, microporous silicone dielectric layer [106]. This yielded a high baseline capacitance with excellent signal quality, enabling a resolution of 0.86 kPa and negligible drift (0.05–0.15% across 25–100 kPa). The sensors also exhibited fast response times (7 ms) and stable sensitivity (2.7–8.4% change at 50–100 kPa).

Together, these results show that knitted capacitive pressure sensors provide fast, stable, and tunable responses through deliberate control of spacer thickness, dielectric properties, and knitted architecture.

Triboelectric and piezoelectric pressure sensors exploit compressive deformation to generate electrical charge. Pressure-sensitive textile patches (Fig. 5a,b), constructed from alternating conductive and non-conductive yarns arranged in cardigan and tuck stitches, have been shown to effectively transduce mechanical loading into electrical signals. As pressure is applied, the contact area between the conductive loop heads and the non-conductive tuck stitches increases, enhancing triboelectric charge generation [117]. Under compression, stresses at the yarn interfaces induce contact and separation events that drive charge transfer, resulting in a measurable voltage output corresponding to the applied pressure (Fig. 5c). These sensors exhibit a pressure sensitivity of 7.84 mV/Pa, a fast response time of 20 ms, and a wide operational frequency range of up to 20 Hz [117]. When integrated into garments, such structures enable pressure sensing at the wrist and chest for applications including respiration and heart rate monitoring (Fig. 5d).

Similarly, compressive deformation in multilayer knitted structures can enhance piezoelectric responses. One such approach employs a yarn composed of twisted electrospun polyamide and conductive nylon, further braided with a polyimide sheath (Fig. 5e) [110]. This architecture forms a three-layer system consisting of a conductive core electrode, a piezoelectric polyamide layer, and an outer protective sheath. When knitted into a fabric (Fig. 5f), the resulting textile functions as an energy-generating sensor, producing output voltages ranging from 0.98 to 1.92 V under applied forces between 3 N and 11 N at a frequency of 4 Hz (Fig. 5g). These yarns can be seamlessly integrated into garments to harvest energy and sense joint motion, movement patterns, and external pressure.

At a larger structural scale, piezoelectric sensing has also been realized using a PVDF nanofilm membrane sandwiched between two knitted three-dimensional electrodes (4×1 rib) and encapsulated within an elastic self-adhesive bandage. This configuration enables stable detection of human motion, including swallowing, joint bending, and foot movement. The sensor demonstrates long-term durability over 3,350 loading cycles, a sensitivity of 0.68 V/kPa, and a wide force detection range from 0.098 N to 724 N [118].

Beyond human wearables, knitted pressure sensors also play a critical role in advancing robotic perception and interaction. Integrating tactile sensing into robotic systems enables richer environmental awareness, allowing robots to perceive contact, interpret physical interactions, and respond adaptively [119, 120]. One representative example by Si et al. explores the use of knitted tactile skins for both human–robot interaction and human-guided robot control [121]. In this work, a machine-knitted pressure-sensitive textile is constructed using an insulated mesh layer sandwiched between two orthogonal arrays of piezoresistive yarns. This architecture forms discrete tactile pixels (taxels) that become electrically active under contact while remaining isolated in the absence of pressure, ensuring accurate and localized sensing. Collectively, these examples illustrate how knitted tactile skins can bridge soft and rigid systems, enabling more intuitive, responsive, and embodied forms of human–robot interaction.

Electrophysiology

Textiles provide an excellent platform for electrophysiological sensing, offering soft, compliant, and comfortable interfaces that can be worn for extended periods. By knitting biopotential electrodes directly into the fabric, these sensors become breathable, flexible, and unobtrusive components of everyday garments. Unlike traditional gel-based electrodes that may cause discomfort or are unsuitable for long-term use, knitted textile electrodes naturally conform to body contours, leveraging the inherent stretch of knitted loops to maintain stable and intimate contact with the skin. Knitted sensors utilized for physiology is summarized with Table 4. Early textile platforms, such as the Wealthy or Wearable Wellness systems, demonstrated that knitted structures could support multimodal biosensing, such as electrocardiogram (ECG), respiratory monitoring, and posture detection through embedded conductive textile layers and knitted electrode patches in everyday garments. The Wealthy sensing platform is comprised of six textile ECG electrodes, implemented as a double fabric layer with the conductive part contacting the skin, and three larger textile electrodes for impedance measurements. The textiles were connected through a multilayer structure with conductive fabric sandwiched between two layers of insulating textiles, allowing for the integration of two temperature transducers and an oxygen saturation (SpO2) sensor [122]. The Wearable Wellness System was used for long-term physiological monitoring, and it utilizes two dry electrodes for ECG (as opposed to Wealthy system's wet electrodes) and one textile based piezoresistive sensor for detection of respiratory activity [123].

More recent work has advanced the materials and knitting technologies used to create these electrodes. Fully knitted dry electrodes using conductive elastomeric fibers (CEF) were produced through melt spinning and directly knitted into wearable garments [124]. The dry textile electrode had a 3D structure: the surface of the electrode was knitted CEFs, a spacer layer made from the tuck stitch for filler, and the bottom layer with polyester yarn for structural support. Of the different CEFs investigated, CSR2, a conductive carbon filler with silicone rubber was chosen for its small diameter (462 μm) and functional properties(max strain of 258.12$\pm$ 26.05%, max stress of 11.99$\pm$1.17, and tenacity, the ratio of maximum breaking force and linear density, or 1.11 $\pm$ 0.11). These electrodes were integrated into underwear for ECG and into a headband for electrooculograms (EOG), demonstrating high comfort and conformity while maintaining signal fidelity comparable to gold-standard gel electrodes. The elasticity of the CEF yarns allowed the knitted electrodes to maintain contact during daily motion, supporting continuous 24-hour ECG acquisition and showing durability across 30 wash–dry cycles. Similarly, knitted electrodes using carbon-nanotube-wrapped cotton/spandex yarns have been explored. It was found that rib-knitted electrodes exhibited superior stability against motion artifacts and improved signal-to-noise ratio compared to woven and braided counterparts, highlighting the advantages of knitted structures in achieving both mechanical compliance and electrochemical performance [125].

Knitting also enables electrodes to be embedded as part of larger sensing architectures. In particular, knitted electrodes can serve as boundary nodes for electrical impedance tomography (EIT), enabling spatially distributed sensing for gesture recognition, posture estimation, and garment self-localization [126] (Fig. 5.h). Yu et al. developed fabric electrodes that can be knitted using intarsia to create discrete conductive patches, while plating connected conductive and nonconductive yarns coursewise. Impedance changes generated by deformation were reflected in variations of spatial contact, pressure distribution, and material stretch. These measurements were captured across the knitted electrodes and used to infer user actions and body positioning. They leveraged machine learning for real-time, active sensing of worn location and gesture recognition (Fig. 5.i). Another work by Motiepor et al. looked at how knitted electrode wires can be implemented in a flexible electroencephalogram (EEG) cap [127] (Fig. 5.j). The electrode wire was knitted directly into the textile (Fig. 5.k), and under stretch, they demonstrated the prototype had a maximum elongation of 110%, and was able to undergo 3200 cyclic elongations at 40% strain. More importantly, it was able to achieve similar results in terms of EEG signals compared to conventional EEG caps (Fig. 5.l). Similarly, the intarsia method was used to create electrodes for a knitted band with eight channels for surface EMG signal sensing (Fig. 5.m-n) in order to control a prosthetic hand. This band was found to achieve a similar EMG signal compared to more commonly used disposable electrodes, and was able to classify between 6 different hand gestures(Fig. 5.o) [128].

Across these examples, knitted electrophysiology sensors illustrate how textile structures, conductive yarn development, and garment-scale integration strategies collectively enable high-quality physiological monitoring. These advances position knitted electrodes as a promising route toward everyday bio-integrated wearables capable of continuous, real-world electrophysiological sensing.

Environmental and chemical

Functioning as the body's immediate interface with the external world, textiles occupy a unique position where internal biochemical signals and external environmental stimuli converge and interact with each other, making them exceptionally well suited for integrated chemical and environmental sensing. Knitted textiles offer a highly adaptable platform for embedding these sensing capabilities at the yarn level, enabling garments to monitor chemicals [129, 130, 131], pH [132, 133], humidity [134, 135], and temperature [136, 137, 138] without compromising comfort or flexibility. Prior works conducted on such knitted chemical and environmental sensors are summarized with Table 4. Such functionality is commonly achieved by functionalizing yarns through chemical soaking, metallic deposition, electro- or melt-spinning, or incorporation of carbon nanotubes, which allows sensing elements to be embedded at the stitch, planar, and structural scales of the fabric. This multilevel integration makes knitting uniquely suited for the next generation of wearable chemical, thermal, and environmental sensing systems.

One such yarn-level integration strategy has been demonstrated using stainless steel and silver-coated nylon fibers to form electroactive regions within a 3D tubular knitted structure. Their design alternated conductive and insulating yarn courses, producing segmented electrode regions within a continuous knit capable of amperometric detection of potassium ferricyanide [139]. Similarly, flexible resistance temperature detectors (RTDs) has been directly embedded into yarns through covering, braiding, and knit-braiding processes (Fig. 5.p), then inlay these sensing yarns into a knitted armband (Fig. 5.q). The integrated RTD yarns offer linear temperature response, with a thermal time constant < 10s and robustness to bending. More importantly, it is able to attain reliable skin-temperature measurement during rested arm temperature (21.7 °C) and arm temperature during exercise (33.3°C - 35.8°C), with a reduction of sensitivity of only 14% [136] (Fig. 5.r).

The development of dual-sensing nanoyarns further illustrates the trajectory toward fully functionalized sensing fibers that can be directly integrated into textile structures. Yin et al. fabricated PU/CNT-based nanoyarns exhibiting strong pH sensitivity (47.8 mV/pH), temperature sensitivity (1.53 % °C), rapid response times (10 s), and high linearity (R^2 = 0.993) [140]. Complementary efforts have explored wetness-sensing yarns in which contact between insulated and conductive segments enables capacitive measurements, while resistance changes along the yarn provide an additional sensing modality. Using electrochemical impedance spectroscopy at fiber crossover points, wetness can be detected through large impedance shifts, with the dry textile exhibiting above $> 10^7\Omega$ that decrease by more than two orders of magnitude upon wetting [141].

Related approaches include microfluidic thread-based sensors incorporating chromogenic reactions for sweat analysis, capable of detecting chloride concentrations up to 10 mM, pH values between 4.0 and 9.0, and glucose concentrations down to 10 μM [142]. While many of these sensing strategies have been demonstrated through weaving or embroidery, they are compatible with knitting-based fabrication. Knitting offers distinct advantages for such functional yarns: its looped architecture provides intrinsic stretchability, porosity, and mechanical compliance, allowing intimate skin contact and efficient fluid transport. By combining the mechanical adaptability of knitted architectures with advances in electrochemical [143, 144, 145], sweat [135, 146], and temperature sensing [147, 148, 137, 138], knitted e-textiles can support high-performance, multimodal sensing systems suitable for continuous chemical and environmental monitoring.

Actuation

Knitting has recently emerged as a powerful medium for programmable actuation, haptic feedback, and embedded computation. Unlike weaving or laminating, knitting inherently creates interlocked, hierarchical geometries capable of large, reversible deformations, local mechanical tuning, and seamless integration of multiple material domains. These properties make knitted architectures particularly well-suited for building shape-changing actuators, soft haptic interfaces, and fabric-based computational systems(Fig.6). Table 5 summarizes prior work on knittable e-textiles for actuation and computation.

Shape-morphing interfaces

Knitted structures have unique capabilities as their looped topology accommodates extreme stretch, torsion, and curvature without structural failure. When combined with thermal, pneumatic, or mechanical stimuli, the morphing properties can be programmed, enabling shape-changing textiles that are soft and wearable. The interdependence among yarn material, stitch pattern, and tension distribution defines a unique design space where morphing behaviors can be embedded directly into the fabric architecture, transforming knitting from a passive manufacturing technique into an active mechanical programming platform. Han and Ahn's Blooming Knit Flowers[149] demonstrated how loop-linked knitting can inherently encode out-of-plane deformations, creating morphing structures that unfold like petals and offering an early example of knitted topology applied to soft robotics. Forman et al(Fig.6 a-c). [150] introduced continuously drawn liquid crystal elastomer (LCE) fibers that can be machine-knitted into textiles capable of morphing in response to heat. This work underscores the potential of 4D knitted materials, where stimuli-responsive filaments enable autonomous bending, twisting, or contracting of the fabric. The development in machine knitting further allows the computational program of geometry and morphing. Rout et al. [151] extended this understanding through Knit-Morphs, a computational framework that bridges stitch geometry and large-scale morphing behavior. This work provides a quantitative foundation for predicting shape outcomes from knit design parameters.

Knitted morphing platforms enable applications ranging from bio-inspired locomotion to adaptive compression garments and architectural or robotic morphing skins. Kim et al. [152] explored knitted morphing for embodied and health-centered applications through KnitSkin [152] and KnitDema [153]. KnitSkin introduced machine-knitted scaled surfaces that mimic the anisotropic friction of biological skin, enabling mechanically programmed frictional morphing for sliding and gripping behaviors. KnitDema extended this approach to adaptive therapeutic compression, using variable stitch density and pneumatic channels for personalized edema relief.

Force actuator

Recent advances in knitted actuation systems demonstrate how textiles can transition from passive substrates into mechanically programmable, force-generating, interactive media. By embedding pneumatic, fluidic, electroactive, and thermally responsive elements directly into knitted architectures, researchers have enabled fabrics capable of controlled deformation and force for adaptive support and embodied interaction [42, 154, 155, 156, 157, 158].

Early explorations in knitted actuators focused on leveraging stitch topology and material composition to encode large-scale shape change. Albaugh et al. introduced a fully digital pipeline(Fig.6 d-g) that replicates the motorized force actuation by the inlaid patterns [42]. This work established knitting as a structural mechanism for generating predictable bending, curling, and expansion behaviors, positioning textile architecture as an active design parameter rather than a passive shell.

The unique knitting topology also enables pneumatic and fluidic actuating approaches, which are the most extensively explored type of knitted force actuators, offering high force output while maintaining softness and compliance. Luo et al. integrated pneumatic channels and conductive yarns within a single knitted layer, enabling simultaneous actuation and sensing in a seamless textile system [154]. Subsequent work refined the structural organization of pressure-driven motion. Elmoughni et al. demonstrated machine-knitted, seam-free pneumatic sleeves that improve robustness and wearer comfort by eliminating glued interfaces; their seamless knitted pneumatic actuators exhibited sufficient curvature under inflation pressures up to 150 kPa, and were capable of grasping objects down to approximately 3 cm in diameter and 125 g of weight, indicating practical force and motion output for wearable assistive devices [155]. Sanchez et al. further extended this concept through 3D knitting, embedding interconnected pneumatic networks that enable multi-segmented, garment-scale shape morphing [156]. Together, these systems illustrate how knitting can simultaneously function as an actuator housing, a constraint mechanism, and a comfort layer.

At finer scales, fluidic force actuation has been embedded directly into fibers. Kilic Afsar et al.'s *OmniFiber* introduced pressurized fluidic fibers (outer diameter $< 1.8\,\text{mm}$) capable of generating forces up to $19\,\text{N}$ at $0.5\,\text{MPa}$, with linear actuation speeds reaching $150\,\text{mm/s}$, enabling rapid, localized deformation and on-body haptic feedback [157]. Phan et al. demonstrated that related fluid-driven artificial muscle fibers can be woven or knitted into textile sheets that achieve elongation up to 65%, area expansion up to 108%, and radial expansion up to 25%, supporting uniform and scalable surface-level contraction across large textile assemblies [158].

Beyond pressure-driven systems, knitted textiles have also supported electrothermal actuation mechanisms, where heat induces controlled deformation or therapeutic effects. By exploiting the thermal response of yarn materials or integrated conductive elements, these systems enable gradual shape change, compression modulation, or muscle stimulation. For example, ReKnitCare combines knitted elasticity with electro muscle stimulation (EMS)operating within typical ranges (tens of milliamps, pulse frequencies on the order of 10–100 Hz) to support rehabilitation and sensory therapy, illustrating how electrically driven actuation can be intimately integrated into wearable textiles [159].

Knitted actuation has been explored as a medium for embodied feedback rather than purely geometric transformation. Fluidic fibers, pneumatic pockets, and EMS-enabled textiles enable tactile cues, vibration, and proprioceptive stimulation directly on the body [157, 159]. These systems leverage the conformability and breathability of knitting to deliver feedback that is spatially distributed, comfortable, and continuously wearable qualities difficult to achieve with rigid or laminated haptic devices.

Haptics

Knitted haptic interfaces reimagine fabric as an active, spatially distributed tactile medium that communicates directly with the body. Because knitted textiles offer conformability and air permeability, they can deliver fine-grained pressure, stiffness, or vibration cues without compromising comfort. By varying stitch topology or integrating responsive yarns, designers can control local mechanical impedance and tactile texture, turning the fabric itself into a spatially expressive feedback surface suited for wearable feedback, rehabilitation, and immersive XR interfaces.

Building on this foundation, Luo et al. [86] introduced Magknitic(Fig.6 h-j), a collection of machine-knitted textures combining passive tactile cues with integrated binary sensing, showing how geometry and yarn composition encode tactile feedback within an interactive textile interface. du Pasquier et al. [160] extend this concept with Haptiknit, a knitted haptic interface that spatially modulates stiffness across fabric regions to produce perceivable pressure gradients. By effectively transforming the textile into a continuous haptic field, the system is capable of transmitting forces up to 40 N with a control bandwidth of 14.5 Hz. Singal et al. [161] further formalized these relationships through a stitch-level mechanical model linking pattern, tension, and material composition to tactile perception, providing a quantitative framework for haptic and comfort co-design. Together, these studies frame knitted haptics as a material-perceptual interface, where feedback is woven into the fabric's mechanism rather than appended as an external actuator.

Knitting structure plays a critical role in shaping the mechanical behavior and actuation performance of textile-based soft actuators. Different knitting techniques introduce structural constraints that create trade-offs between extensibility, force output, spatial control, and fabrication complexity. Inlay knitting, where reinforcement yarns are laid into the fabric rather than fully looped, increases directional stiffness and dimensional stability. This reinforcement improves force transmission and enables controlled bending, as demonstrated in programmable knit actuators that encode deformation through inlaid patterns[42]. However, the added constraint typically reduces extensibility and maximum actuation stroke. Tubular knitting, in contrast, forms seamless three-dimensional structures that naturally accommodate volumetric expansion, making it well suited for pneumatic and body conforming wearable actuators. Seam free pneumatic sleeves demonstrate how tubular knitted architectures can support pressure driven bending while improving robustness and wearer comfort [155]. Jacquard knitting enables stitch level spatial patterning of yarns and knit structures, allowing designers to encode regions of varying stiffness, active/passive material placement, or sensing integration within a single fabric. This spatial programmability supports complex actuation behaviors such as distributed or bidirectional haptic feedback [78].Finally, computerized flat knitting provides a flexible fabrication platform capable of producing shaped, multilayer, and seamless structures, enabling the integration of inlay, tubular, and jacquard strategies within a single textile actuator [154].

Display

Knitted computation has expanded toward textile-level interaction and display (Fig. 7 d-f). Wang et al.'s LuxKnit co-knits electroluminescent yarns with conductive and sensing fibers to fabricate large-area interactive display textiles [162]. The system supports simultaneous capacitive touch input and programmable light emission, achieving luminance levels of up to 93 cd/m^2 while maintaining stable functionality under bending and stretching, with less than 20% brightness degradation at 30% strain. By leveraging machine knitting processes, LuxKnit demonstrates how textiles can serve as scalable, deformable visual interfaces that integrate sensing and display directly into everyday fabrics, enabling garments and soft surfaces to function as interactive information displays.

Beyond textile-level displays, recent advances in fiber-scale electronics and computation further extend the capabilities of computational textiles. Early work embedded digital electronics directly inside fibers, enabling fabrics capable of sensing and performing machine learning inference [163]. Building on this foundation, researchers have introduced chipless electronic fibers that harvest ambient electromagnetic energy and leverage the human body as part of the circuit to support wireless textile-based interactions without rigid chips or batteries [164]. Although the functionality is implemented at the fiber level via dip-coating, the fibers are designed to be integrated into textile structures such as knitted fabrics. More recently, single-fiber computers integrating sensing, memory, and microelectronic components have demonstrated that individual fibers can perform distributed computation, allowing textile networks to collaboratively sense, process, and communicate information [165]. Together, these developments point toward a new class of computational fabrics, where knitted or woven structures not only provide mechanical comfort but also act as programmable substrates capable of sensing, computation, and visual feedback directly on the body.

Computation

Rather than serving as passive housings for electronics, knitted systems are being reimagined as computational media capable of processing, feedback, and control within their very topology(Fig.7). This shift is enabled by advances across multiple scales: fiber-level electronic integration, material-level encoding, and fabric-level interaction design [166, 167, 162, 168, 85]. Through these developments, computation becomes not only an external circuit board but an intrinsic property of the textile, distributing intelligence across yarns, stitches, and layers.

At the hardware integration level, Honnet et al. introduced FiberCircuits, a miniaturization framework for embedding integrated circuits directly within fibers within a width of 2 mm, bridging conventional microelectronics with scalable textile manufacturing (Fig.7 a-c) [166]. This approach enables programmable logic and signal control to be physically drawn into the yarn, supporting hybrid systems that can sense, compute, and actuate within the same structural thread. Complementing this direction, Yang et al. (2024) demonstrated a chipless paradigm using body-coupled conductive fibers that transmit signals through capacitive coupling with the human body [167]. Critically, this mechanism leverages the body's high dielectric and conductive properties, reported as relative permittivity $\varepsilon \approx 78$ and conductivity $\sigma \approx 0.6\ \mathrm{S\,m^{-1}}$, to form an efficient coupling pathway compared to air [167]. By eliminating rigid chips and packaged electronics, this approach enables fully soft, lightweight, and deformable computational fabrics suited for continuous wear.Similarly, Li et al. developed electrostatic smart textiles capable of Braille-to-speech translation, highlighting the potential of textiles as platforms for assistive communication and multimodal feedback [169]. These works show a trajectory from functional yarns to computational fabrics capable of real-time interaction and multimodal feedback.

Together, these efforts demonstrate how knitted materials can embody both input and output modalities in a single structure.

Communication

Body area networks are the data infrastructure for smart textiles and wearable computing, enabling continuous health monitoring and data exchange around the human body [170]. Despite the successful transformation of sensors and actuators into stretchable textiles, as described in the Sensing and Actuation Section, the network's hardware remains rigid; these body area networks depend on small, rigid antenna modules such as Bluetooth Low Energy or ZigBee [171, 172]. This reliance on the rigid antenna often leads to connection failures at the interface with fabric-based soft electronics. Textile stretchable antennas composed of conductive fabrics are promising to transmit and receive radio signals without compromising breathability and stretchability [65, 173, 174]. Conventional textile antennas created through post-additive processes (e.g., printing [175], embroidery [32], or lamination [176]) support complex antenna patterns, but suffer from mechanical instabilities like delamination and limited scalability. In contrast, industrial knitting integrates stretchable antennas directly into the fabric, ensuring mechanical stretchability and mass production.

As detailed in the Knitting Structure section, intarsia and jacquard knitting are suitable for creating knittable antennas because they allow for the direct integration of isolated, simple conductive patterns within a non-conductive fabric base. For example, intarsia enables the single-step fabrication of battery-less RFID tags, which transmit data with ultra-low-power by modulating the reflection of external radio signals, rather than actively generating radio signals [177, 178]. Patron et al. present a knittable RFID tag based on a single-layer dipole antenna (Fig. 8.a), which passively encodes mechanical stretch into the reflective signal strength [179] (Fig. 8b). Such a knittable RFID tag enables comfortable, scalable fabric-based wireless monitoring, eliminating the need for rigid batteries, transceiver circuits, and fragile solder joints. In contrast, jacquard knitting provides pixel-level loop control over multi-layer structures, enabling the precise fabrication of conductive unit cells with a specific radio-wave reflection pattern. By arranging these custom-designed cells into periodic arrays, the fabric functions as a knittable metamaterial for wave manipulation, including beam steering and electromagnetic shielding [180, 46, 181] (Fig. 8.c-d).

Knitting can create not only passive wireless tags but also the wireless reader antenna. Integrating such a reader directly into a garment eliminates external reader constraints, allowing continuous wireless monitoring in everyday environments. Because water-rich tissues absorb high-frequency radiative signals (e.g., UHF, BLE), these textile readers near the body are promising to utilize inductive coils for near-field communication (NFC) [182, 183, 184]. The NFC-based coils enable energy-efficient on-body wireless connectivity by generating near-field magnetic fields that penetrate the body with negligible interaction [185]. While sewing or embroidery can fabricate a flat spiral coil typical of NFC [186], knitting such spiral geometries is difficult due to the structural constraints of loop formation. To overcome this, two alternative knittable coil structures are available.

First, a 3D spiral coil that winds upward along the fabric tube has been proposed by utilizing tubular knitting [187, 188] (Fig. 8.e-f). The placement of the 3D spiral coil is suitable for the wrist or neck, where it can facilitate communication with on-skin coils located at a relatively short distance with 3–5 cm (e.g., wrist and hand, neck and face/ear). Second, a 3D meander coil has also been explored based on tubular knitting [31, 47, 50], which resembles a 3D spiral in structure but alternates its winding direction at every turn (Fig. 8.g-h). Unlike the spiral coil, the meander coil generates a different magnetic field distribution that is confined near the skin surface, while minimizing electromagnetic exposure to deep internal tissues. This localized field distribution makes the meander coil ideal for large-area applications such as the torso, sleeves, and legs, where the meander coil provides a secure and energy-efficient platform for <1 cm skin-to-clothes short communication with distributed on-skin NFC sensor tags [50] (Fig. 8.i-j).

Powering

Reliable energy storage and harvesting are essential for driving the electronics embedded in smart textiles and wearable devices [189, 190]. To resolve the mismatch between traditional rigid batteries or harvesters and soft human skin, the field has evolved from rigid components to flexible films and stretchable elastomers [191]. Unfortunately, the film-based and elastomer-based approaches typically act as impermeable barriers, sacrificing the breathability essential for long-term wearability [192]. Industrial knitting machines are expected to manipulate surface and volume topology to transform functional fibers into highly breathable, hierarchical architectures. For example, knitting enables to customize textured loops for triboelectric amplification, 3D spacer fabrics for kinetic harvesting, controlled thickness for thermoelectric gradients, and seamless tubes for batteries. Such knittable energy harvesters and batteries integrated into textiles can enable self-powered, continuous health monitoring and human-machine interfaces.

Knittable energy harvesters mainly use triboelectric, piezoelectric, and thermoelectric principles, each benefiting from specific knit architectures [193]. Triboelectric nanogenerators (TENGs), which generate electricity via surface friction, are compatible with the superior deformation features of knitted fabrics. For example, Dong et al. employ an interlock knit structure composed of conductive fibers wrapped in PTFE or PA66, where fabric deformation causes the opposing fabric to collapse and contact, thereby generating electricity [194] (Fig. 9.a-b). This design achieves a higher power density under compression ($7.5\,\mathrm{mW/m^2}$) than under stretching ($1.5\,\mathrm{mW/m^2}$), as vertical pressure maximizes contact area more effectively than lateral tension. Other knit structures like rib [195] or interlock [196] have also been explored. Unlike triboelectric nanogenerators, which rely on surface interaction between yarns, piezoelectric nanogenerators (PENGs) generate electricity when the knitted fibers themselves are compressed [118, 197]. At a fiber level, Mokhtari et al. develop a yarn-shaped generator by employing circular knitting to sheathe conductive cores with $PVDF/BaTiO_3$ fibers, achieving $87\,\mathrm{\mu W/cm^3}$ [111] (Fig. 9.c-d). At a fabric level, Anand et al. construct a piezoelectric fabric by using spacer knitting to sandwich PVDF monofilaments between conductive fabrics, concentrating pressure to achieve $11–51\,\mathrm{mW/m^2}$ [53]. Unlike these intermittent body harvesting, thermoelectric generators provide a continuous power source by scavenging heat energy via the temperature gradient maintained across the textile between the human skin and the surrounding environment [198, 199]. For instance, Zheng et al. utilize a 3D spacer knit where vertical carbon-nanotube yarns serve as both vertical pillars for electricity generation and insulating spacers, generating $51.5\,\mathrm{mW/m^2}$ with a temperature difference of $47.5\,\mathrm{K}$ [200] (Fig. 9.e-f). Finally, there is increasing interest in developing hybrid systems that combine these methods to improve overall efficiency [201, 202].

While the knittable energy harvesters provide comfortable self-powered energy storage in the e-textiles, their harvesting capability fluctuates significantly depending on external environmental conditions and user activity. As reliable textile-based power sources, fiber-shaped batteries such as lithium-ion [203, 204] and solid-state zinc-ion fibers [205] are typically employed. Furthermore, textile-based supercapacitors have also been gaining attention for e-textile applications requiring rapid charging and high instantaneous power output. Unlike the fiber-based chemical design of the battery, the textile-based supercapacitor needs a physical design of textile-based electrodes and separators to maximize surface area. Therefore, knitting is preferable because knitting allows for the fabrication of hierarchical and multilayered textile patterns, which significantly amplifies the available surface area for charge storage. Levitt et al. use intarsia knitting to interlace MXene-coated cotton yarns into a dense interlock rib structure, creating 2D flat electrodes that achieve a high capacitance of $707\,\mathrm{mF/cm^2}$ [206] (Fig. 9.g-h). To enhance mechanical stability under pressure, Zhang et al. introduce a 3D spacer knit architecture with $415\,\mathrm{mF/cm^2}$, where stiff vertical polyester monofilaments are knitted between outer electrode layers with MXene-coated nylon multifilaments [207]. The polyester spacer yarns function as a physical separator capable of mechanical cushioning, effectively preventing short circuits and retaining $97\,\%$ of capacitance even after 1000 compression cycles at $55\,\%$ strain. Unlike simple yarn-based supercapacitors whose small surface area limits capacitance around tens of $\mathrm{mF/cm^2}$ [208, 209], the knittable supercapacitors achieve over ten times higher capacitance performance by utilizing the expanded textile surface area.

Finally, knitted textiles serve as near-field wireless power hubs for skin devices, such as ultra-thin epidermal devices, which often lack the volume and space for the equipped bulky batteries. To implement energy-efficient, scalable wireless powering textiles, a low-loss and stretchable conductor such as liquid metal (e.g., eGaIn: $3.4 \times 10^6\,\mathrm{S/m}$ [210]) is promising [210, 211], because standard metal-coated conductive yarns have relatively high resistance ($\sim 10^5\,\mathrm{S/m}$) that degrades power transfer efficiency. To embed such fiber into the textile, plate knitting is useful to fabricate hollow tubular channels within the garments, which are filled with liquid metal-filled tubes. For example, Takahashi et al. present safe, body-scale wireless powering garments based on a meander coil composed of the liquid metal tube [47, 212] (Fig. 9.i-j). As described below, the meander coil is specifically designed to localize the strong electromagnetic field near the skin surface, enabling the suppression of the specific absorption rate (SAR), established by ICNIRP, which is a measure of how much radiation energy is absorbed by the body per unit mass when using wireless devices. The evaluation shows 2.5 W-level power delivery to advanced wearable devices at 25 % DC-to-DC efficiency, while maintaining the SAR below the 2.0 W/kg limit for localized human exposure and the 0.08 W/kg limit for whole-body human exposure. Therefore, the meander-coil-based inductive power transfer system enables safe, Watt-class power delivery for high-performance wearable electronics. In addition to inductive approaches, body-coupled capacitive power transfer leverages the human body's high permittivity as a conductive path to deliver energy. For example, Song et al. present a body-coupled electrical stimulation system that uses a knittable dual-layered electrode socks that can harvest ambient electromagnetic noise from electronics and static electricity from physical activity. By concentrating localized electric fields through potential distortion, these socks directly stimulate muscle fibers by activating voltage-gated ion channels [213] (Fig. 9.k-l). Note that the summary table for knittable e-textiles with communication and powering functionality is provided in Table 6.

Applications

Building on the material, structural, and electronic capabilities described above, knitted e-textiles enable a broad range of application domains that extend far beyond conventional wearable devices. These capabilities enable garments and soft structures that can sense motion, physiology, and touch; respond through actuation or feedback; and operate autonomously through embedded energy and communication systems. The following sections survey how these integrated functionalities manifest across key application areas, including activity and gesture recognition, physiological monitoring, interactive wearables, and soft robotics.

Activity and gesture recognition

Several non-textile activity-monitoring approaches, such as IMUs, optical motion-capture, and rigid pressure sensors, work well in certain scenarios but may not be the best option for wearable systems that have to fit around the curves of our bodies, maintain accurate sensing during large-range movement, and for long periods of time. Knitted sensors are well suited to activity monitoring on humans because of their intrinsic elasticity and breathable nature. These mechanical advantages reduce motion artifacts and improve signal continuity compared to stiff sensors. In this way, knitted sensors can prioritize sensitivity and accuracy without compromising conformability and comfort.

Knitted strain and pressure sensors have been widely used to capture joint movement, posture, and gesture by embedding sensing elements directly into garments. Gloves (Fig. 10.a), sleeves, and lower-body garments (Fig. 10.b) can track finger flexion, joint angles, and gait patterns (Fig. 10.c) while remaining unobtrusive to the wearer. By adjusting knit architectures, sensor sensitivity can be tuned to support both fine-grained gestures and large-amplitude movements, enabling applications ranging from hand gesture recognition to full-body activity classification [214, 104, 215].

Such systems are particularly relevant for exercise monitoring and rehabilitation, where accurate tracking of complex joint motion is required without restricting movement. Knitted sensors integrated into vests, pants, or footwear have been shown to capture shoulder activity, knee motion, and foot pressure distributions (Fig. 10.d), supporting classification of movement patterns and biomechanical states while preserving a low-profile, wearable form factor [216, 55, 217, 218]. These approaches highlight how knitting enables continuous activity sensing without the bulk or discomfort of rigid sensor assemblies.

Beyond human-worn systems, knitted sensing has also been explored for human–robot interaction and robotic perception. Knitted robotic skins distribute pressure and deformation sensing across soft surfaces, enabling robots to detect contact, compression, and environmental interaction in confined or occluded settings. When combined with human-worn knitted garments, these systems support gesture-based control and shared tactile understanding between humans and robots (Fig. 10.e)[121, 51].

Physiological sensing and intervention

Knitting provides a compelling platform for physiological sensing by enabling electrodes and sensors that conform closely to the body while remaining soft, breathable, and suitable for long-term wear. Unlike conventional rigid or gel-based electrodes, knitted sensors integrate directly into garments, improving comfort, reusability, and skin compatibility while achieving signal quality comparable to traditional approaches [219, 124]. This makes knitted textiles particularly well suited for continuous physiological monitoring in everyday, mobile contexts.

Knitted physiological sensors have been used to capture electrophysiological, cardiovascular, and respiratory signals by leveraging pressure, strain, and impedance changes within looped structures. Garments such as chest bands, undergarments, and head-worn textiles (Fig. 10.f) enable unobtrusive acquisition of ECG, EOG, and respiratory activity while maintaining stable skin contact during movement [126, 124, 179, 220]. The inherent elasticity of knitted structures allows sensing elements to adapt dynamically to body motion without constraining the wearer.

For applications involving significant muscular activity, knitted electrodes offer robustness under deformation while preserving signal fidelity. Their ability to stretch and recover helps maintain consistent electrode–skin contact during speech, exercise, or expressive movement, enabling reliable acquisition of surface electromyography and related signals in scenarios where rigid sensors would fail [221]. These properties position knitting as an effective substrate for physiological sensing in real-world, non-sedentary use.

Beyond passive measurement, knitted physiological systems can also integrate actuation and feedback. By combining sensing electrodes with soft actuators or electrical stimulation elements, knitted garments can support rehabilitation, intervention, and closed-loop interaction while avoiding the bulk and discomfort of conventional systems [222, 223]. This integration enables physiological monitoring to be coupled directly with responsive feedback within a single textile form.

Knitted textiles have also been explored for thermal and chemical sensing, including skin temperature and sweat-based measurements. By placing temperature-sensitive elements or chemical sensors in close proximity to the skin, knitted architectures support biologically meaningful sensing while preserving comfort during prolonged wear [224, 225]. These examples highlight the versatility of knitting for multimodal physiological sensing across diverse environments and activity levels.

Interactive wearables

Knitting enables interactive wearables with a degree of form factor customization, spatial resolution, and comfort that is difficult to achieve with rigid electronics or laminated textiles. The loop based construction allows mechanical properties such as elasticity, thickness, and surface texture to be locally programmed at the stitch level, enabling garments that conform closely to the body while supporting high resolution sensing and tactile feedback. As a result, knitted wearables can integrate interaction directly into clothing, turning fabric into a continuous interface rather than a collection of discrete devices.

Knitted textiles have been explored as interactive surfaces. Knitted haptic interfaces distribute tactile cues across the body by leveraging spatial variation in stiffness, pressure, or surface texture. Luo et al. introduced Magknitic, which combines ferromagnetic yarns and knitted structures to create passive tactile feedback and binary touch sensing within garments [86](Fig. 11.a). du Pasquier et al. further demonstrated how stitch-level control over mechanical impedance can render spatial stiffness patterns as wearable haptic cues, enabling fabrics that communicate information through pressure and resistance rather than vibration or motors [160]. These works illustrate how knitted wearables can deliver subtle, spatially continuous feedback that aligns with the body's natural perception.

Furthermore, knitted wearables have been explored as soft input interfaces that capture body motion, gesture, and touch. By integrating conductive, piezoresistive, or impedance-sensitive yarns into elastic knit structures, garments can sense joint movement, hand posture, or surface contact while remaining unobtrusive and camera-free. Such sensing garments function as embodied controllers, enabling interaction through natural body movement rather than handheld devices (Fig. 11.b-e). This approach has been applied to gesture recognition garments, glove-based interfaces, and body-mounted controllers, where knitting enables dense sensor placement while preserving stretch and comfort [55, 126].

Beyond sensing and feedback, knitting also enables system-level interaction by supporting distributed powering and communication within garments. Takahashi et al. demonstrated wireless powering garments by integrating near-field power transmission coils directly into knitted textiles using plate knitting and liquid-metal-filled tubular channels [47, 212]. By embedding deformable liquid metal conductors within the knitted tube holder, the garment can wirelessly deliver power to distributed LEDs and sensors across the body surface without rigid wiring or localized batteries. This approach highlights how knitting can function not only as an interactive interface, but also as an enabling substrate for body-scale interactive systems, where sensing, feedback, and powering are seamlessly co-located within a soft, wearable form factor.

Overall, interactive knitted wearables demonstrate how knitting can unify form, sensing, and feedback within a single textile substrate. By embedding interaction at the material and stitch level, these systems move beyond add-on electronics toward garments that are inherently interactive, expressive, and suited for everyday use.

Soft robotics

Knitted textiles have been a compelling material platform for soft robotics, offering a unique combination of compliance, structural programmability, and garment-scale manufacturability. Unlike conventional soft robots fabricated through molding or lamination, knitted robotic systems leverage loop-based architectures to achieve large, reversible deformations while maintaining breathability and mechanical robustness. This makes knitting particularly well-suited for soft robots that must safely interact with humans, adapt to complex geometries, or operate in close contact with the body. Early work demonstrated that knitted topology itself can encode complex robotic motion. Han and Ahn's Blooming Knit Flowers (Fig. 11.f) showed how loop-linked knitting structures generate out-of-plane morphing and petal-like actuation, establishing knitting as a structural mechanism for soft robotic deformation rather than a passive skin [149]. Building on this insight, Rout et al.'s KnitMorphs framework (Fig. 11.j) introduced computational modeling tools that link stitch geometry to large-scale morphing behavior, enabling systematic design and prediction of knitted soft robotic motion [151]. Knitting has since been combined with active materials and embedded actuation to expand robotic functionality. Forman et al.'s FibeRobo (Fig. 11.g) integrated continuously drawn liquid crystal elastomer fibers into knitted fabrics to achieve thermally driven, distributed actuation and programmable 4D robotic motion [150]. In parallel, pneumatic and fluidic strategies embed actuation within knitted shells, where the textile simultaneously serves as actuator constraint and structural body [42, 154, 156]. At finer scales, fluid-driven artificial muscle fibers (Fig. 11.i) have been woven or knitted into textiles to produce uniform, scalable contraction, supporting garment-scale soft robotic assistance and wearable robotics [158, 157]. Beyond actuation, knitted textiles have also been explored as infrastructural skins for soft robotic systems. Machine-knittable pressure-sensitive skins enable distributed tactile perception for human-robot interaction and lead-through teaching, allowing robots to respond to touch and physical guidance [120, 121]. Complementarily, Kanada et al. proposed a knittable wireless powering skin for a joint-repositionable snake robot, distributing energy along the robot body without rigid wiring and enabling lightweight, reconfigurable locomotion [226]. Knitted soft robotics has further extended into health and assistive domains, where adaptability and personalization are critical. Kim et al.'s KnitSkin explored mechanically programmed frictional morphing for embodied interaction, while KnitDema demonstrated personalized therapeutic compression for edema treatment through variable stitch density and pneumatic control [152, 153]. Together, these works position knitting as a foundational fabrication paradigm for soft robotics, unifying structure, actuation, sensing, and power delivery within a single textile architecture. This integration enables soft robots that are lightweight, conformable, and seamlessly embedded into everyday human environments

Soft artificial muscle

Knitted textiles are also increasingly investigated as platforms for soft artificial muscles, where textile architectures themselves function as scalable force-generating actuators. Textile based artificial muscles leverage the anisotropic mechanical properties and structural programmability of fabric architectures to convert internal pressure or material deformation into mechanical output. For example, recent work on biaxial fabric pouch motors (BFPMs) demonstrates how textile structures can be engineered to produce significant contraction forces while remaining lightweight and mechanically robust. Yilmaz et al. proposed a scalable fabrication method that utilizes computerized knitting and textile reinforcement patterns to rapidly produce pouch like actuators capable of generating substantial force and displacement comparable to conventional pneumatic artificial muscles [227]. Because the textile structure simultaneously acts as the actuator body and mechanical constraint, such systems can be manufactured efficiently using established textile production pipelines while preserving the compliance and conformability required for wearable robotic systems.

Beyond pouch-based architectures, fiber-level artificial muscle systems have further expanded the design space of textile actuators. Fluid driven textile muscle fibers can be woven or knitted directly into fabrics to produce distributed contraction across large textile surfaces, enabling scalable actuation embedded within garments [158, 157]. These fiber based actuators achieve high power to weight ratios while remaining soft, lightweight, and breathable, making them particularly suitable for wearable soft robotics and assistive technologies. When integrated across garment scale textile structures, such artificial muscles enable adaptive compression, posture assistance, and motion augmentation while preserving comfort and mobility. Together, these advances highlight how knitting and textile fabrication techniques can support scalable artificial muscle systems, enabling soft robotic actuation to be seamlessly integrated into everyday clothing and human-centered robotic devices.

Outlook and conclusion

Looking ahead, the continued evolution of knittable e-textiles will be driven by advances across materials, structures, and systems. At the fiber level, new functional materials will expand the sensing, actuation, and energy capabilities that can be embedded directly within yarns. At the structural level, increasingly sophisticated fiber and knitting architectures will enable precise spatial organization, mechanical programmability, reliability, and integration of many functions within a textile substrate. At the system level, the convergence of multimodal and adaptive sensing-actuation systems and embedded computation supports more intelligent and context-aware textile behaviors. Complementing these developments, advances in computational design and digital fabrication enable the translation of complex functional requirements into manufacturable knit structures, supporting scalable and customizable production. Together, these directions point toward intelligent, seamlessly integrated e-textile technologies.

Fiber materials and properties

Advances in fiber materials present a critical opportunity to extend knitted e-textiles beyond single-modality sensing toward truly multimodal and intelligent systems. While much prior work has focused on strain, pressure, or basic physiological monitoring, recent developments increasingly enable the detection of a broader range of physical, chemical, and environmental stimuli, including temperature, humidity, biochemical markers, radiation, and airborne contaminants [141, 144]. These capabilities are driven by progress in conductive, semiconductive, and ionic fiber technologies fabricated through scalable approaches such as thermal drawing, wet spinning, coating, and multilayer assembly [140, 134].

Recent work on multimaterial and multifunctional fibers further expands this landscape by integrating multiple sensing and actuation modalities within a single filament [8]. Such fibers can combine capacitive, resistive, and piezoelectric sensing, or incorporate actuation mechanisms such as fluidic, pneumatic, shape-memory alloy, or thermally responsive elements [24]. By co-locating these functionalities at the fiber level, complex sensing and actuation behaviors can be achieved without increasing system-level complexity.

Advances in fiber architectures have also enabled the integration of sensing, signal transduction, and even elementary computation within a single continuous filament [9]. These developments underpin emerging concepts such as fiber-based computing systems [166], in which computation and sensing are embedded directly into textile structures rather than added as discrete electronic components. To further advance this paradigm, continued progress in micro- and nanoscale fabrication techniques, particularly those compatible with complex non-planar surface and fiber drawing, will be essential for increasing functional density and computational capability [228].

Equally important are efforts to improve the robustness and longevity of functional fibers for knitting and real-world use. During knitting, yarns are repeatedly bent around needle hooks and sinkers during loop formation. Because needle spacing scales with machine gauge (e.g., 2–4 mm for 7–12 gauge machines), the resulting yarn curvature can correspond to bending radii on the order of 0.5–2 mm, depending on gauge, needle geometry, and yarn tension [14, 229]. Combined with friction at machine elements and transient yarn tension during stitch formation, these conditions impose substantial mechanical stresses on functional yarns and conductive coatings. Experimental studies have quantified the mechanical impact of knitting on yarn properties. For example, Iqbal et al. evaluated several common yarn materials before knitting and after being unraveled from knitted fabrics, showing that the knitting process can induce measurable mechanical degradation. In particular, the bending modulus decreased by 3–30% and the tensile modulus by 2–10% after knitting [230]. These results indicate that the repeated bending, friction, and mechanical loading inherent to knitting can alter yarn mechanical behavior and potentially accelerate degradation in conductive coatings or functional layers used in electronic textiles. Strategies such as protective coatings, stretchable conductive architectures, and mechanically resilient fiber designs may therefore help mitigate these effects and improve the durability of functional yarns during knitting and subsequent use.

Beyond fabrication, durability challenges continue during garment use and maintenance. In wearable applications, textiles integrated around body joints typically experience 10–40% strain during normal movements, and in some cases up to 50% strain in highly deformable regions such as elbows or knees, depending on garment fit and fabric elasticity [71, 231]. To accommodate these deformations and provide safety margins, many wearable strain sensors are designed to withstand large strain ranges exceeding 100%, ensuring reliable operation during repeated body motion [232]. Knitted e-textiles are often evaluated under repeated mechanical loading to simulate daily body motion, with some systems demonstrating stability over up to 100,000 strain cycles [117, 54]. However, cyclic stretching can progressively increase contact resistance between conductive yarn segments, induce fiber fatigue, or create intermittent electrical discontinuities in functional networks. Knitting architectures can play an important role in mitigating these effects: through pattern engineering and reinforcement zones, strain and stress on functional yarns can be redistributed and reduced, improving the electromechanical stability of knitted e-textiles. In addition to mechanical and electrical test, the electrochemical test is useful to evaluate the durability of knittable power storage such as supercapacitor. For example, repeatable charge-discharge cycles are employed to show the stable performance of knittable supercapacitor after 10,000 charge-discharge cycles [206].

Washing introduces combined mechanical, chemical, and thermal stresses that can degrade conductive pathways and interconnects, making it one of the primary barriers to large-scale deployment of electronic textiles [233]. For example, conductive threads without protective encapsulation can experience significant resistance increases during repeated washing cycles. Experimental studies show that while both protected and unprotected conductive threads exhibit an initial linear increase in resistance during the first several wash cycles, the resistance of unprotected threads increases exponentially after approximately 10 cycles, reaching values more than 70 times the initial resistance after 50 wash cycles [234]. In contrast, conductive threads protected with TPU encapsulation exhibit only a gradual and stable resistance increase, remaining within acceptable ranges throughout the washing tests. Protective encapsulation layers and hybrid textile integration strategies can therefore play an important role in improving wash durability and environmental stability by shielding conductive pathways from abrasion, moisture, and chemical exposure during wear and laundering.

Looking forward, there is significant opportunity in developing biocompatible, biodegradable, and environmentally resilient fiber systems suitable for long-term deployment in close contact with the body and natural environments [235, 236]. Bio-derived materials such as cellulose, silk fibroin, chitosan, and alginate offer promising pathways toward electronic textiles that are both skin-compatible and environmentally sustainable [237]. Such fibers could enable wearables that monitor health or environmental exposure while reducing long-term textile and electronic waste through biodegradation and decomposition after their functional lifetime [238].

Knitting architecture and manufacturability

Beyond material composition, knitting architectures offer a powerful framework for organizing and scaling functional fibers. Advanced knitting techniques, including multi-bed knitting, inlay structures, and multi-yarn feeder configurations, enable spatially programmable architectures analogous to multilayer printed circuit boards. A particularly promising direction lies in whole-garment and solid knitting, in which three-dimensional, volumetric textile structures are produced rather than surface-bound fabrics [57, 21]. Unlike conventional planar knits, this allows functional elements to be embedded throughout the thickness of a material and in three-dimensional forms, enabling sensing, actuation, and load-bearing capabilities to be distributed across a volume. These techniques allow yarns to be selectively routed, layered, and isolated within a single textile, enabling complex circuit topologies and functional zoning without the need for rigid substrates or post-assembly processes [3].

Such architectural control enables multimodal sensing within a single textile platform, supporting the simultaneous measurement of strain, pressure, temperature, and other stimuli while minimizing cross-talk between sensing channels. Shape-changing and haptic yarns can also be integrated alongside sensing elements, enabling closed-loop control. By encoding sensing and actuation regions directly into stitch topology and yarn placement, knitted systems can localize functionality and reduce reliance on dense wiring or matrix-based readout schemes.

Most current textile antennas are small and fabricated with lossy materials, making them naturally insensitive to the RF fluctuations caused by fabric wrinkles or body movement [179]. However, as the antenna moves toward high-conductivity and large-scale architectures like meander coils [47], antenna performance, i.e., impedance across frequencies, is inevitably sensitive to mechanical deformation. Therefore, the development of deformation-aware RF design will be required to ensure stable communication. This involves either active impedance compensation using switching-based matching circuits [47] or utilizing passive stabilization where stretchable dielectric materials passively suppress resonant frequency shifts of the stretchable coil during strain [239]. Such advancements would allow for robust and high-performance wearable wireless networks.

From a manufacturing perspective, industrial knitting machines are typically optimized for throughput and consistent fabric formation rather than for preserving fragile functional materials. Yarn tension during knitting varies with yarn type, stitch structure, and machine parameters, with experimental measurements reporting tensions of approximately 9–26 cN (0.09–0.26 N) in the knitting zone for common textile yarns [240]. As yarn passes through different machine zones and interacts with needles and previously formed loops, these tension fluctuations introduce friction and mechanical loading during stitch formation. Machine parameters such as tension, take-down speed, and gauge therefore strongly influence knitting forces and fabric structure, and excessive tension can increase frictional stress on yarns [241]. Although reducing machine speed or yarn tension can help protect fragile functional fibers, these adjustments often reduce manufacturing throughput. In practice, a compromise must therefore be reached between knitting process and yarn durability.

Beyond manufacturing parameters, future work in the field may also benefit from clearer benchmarking practices specifically tailored to knitted e-textiles. Consistent reporting of experimental parameters beyond machine settings, such as encapsulation methods, electrical contact strategies, washing protocols, cyclic loading conditions, and signal drift metrics, could improve reproducibility and enable more meaningful comparison across studies. A review on e-textiles has also emphasized the need for standardized characterization protocols, including evaluation of biocompatibility, thermal and tactile comfort, aging behavior, performance, and sustainability [242, 243]. Building on these considerations, Shuvo et al. propose a universal testing roadmap for e-textile systems aligned with ongoing standardization efforts from organizations such as American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC) [242].

Extending such benchmarking frameworks to knitted architectures could help establish more consistent evaluation practices and accelerate the development of scalable and reliable knitted e-textile systems.

Finally, we acknowledge the inherent limitations of knitting when compared to other textile manufacturing approaches. Weaving enables higher structural density and precise row–column matrices, allowing tighter control over spatial resolution, dimensional stability, and functional fiber alignment—features that are advantageous for high-density interconnects, antennas, and matrix-addressable sensing arrays [11]. Non-woven and printed textile systems, in contrast, can more readily accommodate bulk material deposition and composite layering, which are particularly well suited for other classes of functional e-textiles [12, 15]. In this context, hybrid textile systems may also offer a promising pathway toward garments that integrate complementary electrical and mechanical functionalities [244].

Scan-to-knit for personalized e-textiles

Advances in knittable e-textile research allow for the seamless incorporation of various sensing and therapeutic capabilities into everyday textiles with a single production step. Such knittable e-textiles can enable personalized healthcare tailored to the unique physiological needs of individuals [90, 245, 246]. To realize this vision, computational machine-knitting design could be useful by directly converting the user's body and movement data into precise knitting instructions that account for the fabric's stretch and deformation. This automated process embeds sensing functionality directly during fabrication, eliminating the need for manual assembly. Furthermore, the integration of this computational design with the 3D knitting machine can facilitate a shift away from standard sizing and wasteful "cut-and-sew" processes to sustainable, personalized "scan-to-knit" e-textiles with minimal material waste. While alternative computational designs, such as parametric [247, 248, 249, 250] or inverse [251] design, focus on the adjustment of generic stitch templates or estimation of stitch patterns to match a target picture, the scan-to-knit design builds a digital second skin by mapping every stitch directly onto the user's real-world 3D body data.

Fig. 12.a illustrates an end-to-end workflow example of the scan-to-knit pipeline, which translates individual physiological data into precise fabrication instructions through three steps [38, 40, 252, 253, 254]. The first process, geometry acquisition, begins with inputting 3D data of the user's anatomy. This can be achieved through various methods including structured light scanning, photogrammetry using multiple cameras, or even utilizing existing CAD models with anthropometric data. The resulting output is typically a point cloud or polygonal mesh representing the body surface. Then, this 3D surface is converted into discrete loop rows (dicing) and needle instructions (transfer planning). This conversion is facilitated by an intermediate Stitch Mesh [255], a topological representation that maps the continuous 3D geometry into a discrete grid of individual stitches. Leveraging this framework, the stitch-based physical simulation can be employed to capture yarn-level interactions such as non-linear bending, twisting, and friction [254]. By modeling these complex mechanical behaviors, the system can precisely predict electrode displacement and skin-contact stability under dynamic body movement. The final output stage is fabrication planning, where the optimized instructions are compiled into machine-readable code [40]. This code manages high-precision movements of slide needles and multi-bed configurations to produce a seamless, three-dimensional garment.

All-in-one knittable e-textiles

This review describes knitting as programmable architecture capable of seamlessly routing sensors, actuators, computational elements, data, and power across the entire fabric. Such knittable e-textiles have the potential for multi-modal body-scale e-textiles. Current discrete wearables, such as smartwatches and rings, face fundamental limitations because they attempt to monitor the body's large-scale, distributed signals from a single point.

Additionally, their rigid and bulky form factors often cause discomfort during prolonged use. In contrast, 3D knitted structures provide a conformal and breathable platform that can distribute large-scale sensor arrays [117] across the entire textiles. This ensures the stable electrode-skin contact required for high-fidelity sensing while allowing unrestricted movement. By interlacing functional fiber-shaped devices [256, 257] or actuators [42, 258], these textiles can also support high-performance computing capabilities directly within the garment. Ultimately, by routing energy harvesters [196], batteries [207], and data and power networking [31, 47] during the knitting process, 3D knitting could create seamless "all-in-one" e-textiles (Fig. 12.b).

Intelligent soft wearables

Toward intelligence, soft wearables must move beyond passive material properties to support closed-loop interaction [259]. This requires three tightly coupled layers: embedded sensing to capture kinematic, biomechanical, and contact-rich signals directly from the body; material-aware signal processing and modeling to interpret these signals despite noise, deformation, and inter-user variability; and on-body or distributed actuation and feedback to enable real-time guidance, correction, or augmentation of human action. Importantly, intelligence in this context is not solely computational; it emerges from the co-design of material structure, sensing layout, and algorithms that explicitly account for the mechanics and constraints of soft substrates.

Advances in fiber and textile based fabrication are increasingly enabling sensing, computation, and communication to be embedded directly within fabrics themselves. As more functional elements are integrated at the fiber and yarn level, textiles begin to operate as distributed computational systems rather than passive carriers of electronics [9]. In such architectures, sensing, signal processing, and actuation are spatially distributed across the garment, allowing local adaptation, processing, and scalability [260, 261]. This distributed intelligence could also enable textiles to dynamically allocate power, communication bandwidth, and processing resources in response to changing physiological states or environmental conditions.

As artificial intelligence continues to advance rapidly, we envision its integration into knitted soft wearables across multiple dimensions. AI-driven models can analyze the high-dimensional, multimodal data captured by soft textile sensors, enabling robust inference of user state, intent, and context under real-world conditions [51]. A variety of machine learning approaches have been explored to interpret the longitudinal, multimodal, and scalable data captured by knitted sensing interfaces. For example, time-series models such as recurrent neural networks (RNNs) and long short-term memory (LSTM) networks are commonly used to capture temporal dependencies in physiological and motion signals [262]; convolutional neural networks (CNNs) have also been applied to learn spatial–temporal patterns [51]; and contrastive learning has been used to learn robust representations from multimodal wearable data with limited labeled supervision [263]. The integration of AI can also help mitigate calibration drift, inter-subject variability, and motion artifacts in sensing signals from soft, flexible knitted structures. Beyond perception, AI enables closed-loop adaptation by predicting human intention, and optimizing control: haptic feedback can be modulated for motor learning or rehabilitation [160]; pneumatic or shape-changing structures can provide responsive assistance or resistance [153, 157]; and biofeedback systems can regulate breathing, posture, or stress through continuous physiological monitoring [221, 264].

The integration of AI with functionally integrated knitted textiles transforms soft wearables from passive sensing garments into intelligent, responsive systems that actively support human performance, rehabilitation, and interaction [265, 266, 267]. It will transform soft wearables from sensing garments into adaptive systems. These systems do not merely observe the body but actively engage with it, supporting movement, enhancing perception, and augmenting human capability. Furthermore, through on-device learning embedded within the knitted interface, computation and intelligence can be seamlessly integrated into the material itself [262]. Therefore, they establish a foundation for a new class of intelligent, embodied technologies that seamlessly integrate material, computation, and human experience.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

N/A.

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Author contributions

R.T., Y.L., and I.W. conceptualized the review. R.T., H.H.C., H.M., Y.L., and I.W. revised and edited the manuscript. T.Y., T.S., and Y.K. supervised the work. R.T. and I.W. prepared Figures 1–2 and 12; R.T., W.Y., and I.W. prepared Figure 3; H.H.C. and I.W. prepared Figures 4–5 and 10; H.M. and Y.L. prepared Figures 6–7 and 11; and R.T. prepared Figures 8–9. All authors contributed to the preparation of the manuscript.

Competing interests

The authors declare no competing financial or non-financial interests. Takao Someya is an Editorial Board Member of npj. Flexible Electronics. Takao Someya was not involved in the journal's review of, or decisions related to, this manuscript.

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Figures and tables

Table 1: Related reviews and their main focus.

Focus areas	Ref.
General e-textile review (from fiber to garment, from modality to application)	
Comprehensive knitted e-textiles • Multiscale review from fibers to garments for knittable e-textiles • Identification of current technical limitations and challenges • Framework for integrating system-level intelligence into e-textiles	**Ours**
Enabling technologies for e-textiles • General review from fiber to garment for various types of e-textiles • Discussion on cross-cutting challenges and future application landscapes of e-textiles.	(2014) [34], (2016) [268], (2018) [6], (2021) [24], (2022) [172], (2024) [15], (2025) [244, 269]
Enabling technologies for smart fibers • Review how smart, functional fiber can be integrated into e-textiles • Review about potential application of smart fibers	(2014) [34], (2025) [235, 270]
Specific e-textile review (application-specific, modality-specific, material-specific)	
E-textiles for **healthcare**	(2023) [144, 271], (2025) [246, 272]
E-textiles for **strain/pressure sensing**	(2019) [87], (2022) [273], (2023) [59], (2025) [274, 275]
Knitted e-textiles for **sensor**	(2020) [82]
Fabrication technologies of **woven** e-textiles	(2025) [72, 276]
E-textiles for **actuation**	(2018) [277], (2021) [24], (2024) [278, 279]
E-textiles for **antenna**	(2017) [177], (2024) [173, 181]
E-textiles for **energy harvesting**	(2016) [201], (2020) [193], (2024) [190]
E-textiles for **supercapacitor**	(2022) [280], (2024) [281]
E-textiles for **optoelectronics**	(2019) [8]
PEDOT:PSS-based e-textiles	(2022) [37]
MXene-based e-textiles	(2025) [282, 283]
Graphene-based e-textiles	(2025) [284, 285]

Table 2: Summary of knittable e-textiles for touch and strain sensing.

Type	Application	Materials	Knitting structure	Performance	Ref.
Touch Sensing					
Capacitive touch sensor	Activity and gesture recognition	Carbon fiber monofilament [83], stainless steel composite yarn [75]	Interlock, spacer [83], Intarsia [75]	• Response time between 10 - 70 ms [83] • Response time of ∼ 80 ms[75]	[83, 75]
Capacitive proximity sensor	Activity and gesture recognition	Silver-coated yarn	Intarsia	• Proximity detection range up to 10 cm	[45]
Resistive touch sensor	Activity and gesture recognition	Silver-coated polyester, stainless steel yarns [84]	Interlock and tubular [76], Jacquard [84]	• Resistance decrease from 335 to 295 Ω under a 9.5 cm displacement [76] • Resistance decrease from 190 to 25 $k\Omega$ with increasing pressure from 0 to 17.5 kPa [84]	[76, 84]
Triboelectric touch sensor	Activity and gesture recognition	Silver-coated yarn [79] triboelectric yarn (+: Ag-Cu alloy coated with polyurethane (PU), copper-coated with PU, silk, PA66, −: acrylic , PTFE) with SS [80]	Plain [79, 80], tubular, rib [80]	• Output voltage of ∼ 19 V at 1 Hz [79] • Output voltage of .95 V at 1 Hz[80]	[79, 80]
Magnetic touch sensor	Gesture recognition	Magnetoactive fiber and silver-coated copper [78], Stainless steel composite yarn, and permanent magnet [86]	Jacquard [78], tubular [86]	• Sensing and haptic feedback functions up to 100 Hz [78] • Binary sensing with passive haptic feedback functions [86]	[78, 86]
Strain sensing					
Piezoresistive strain sensor	Activity monitoring	Carbon and aluminum fiber [103], Silver-coated yarn [102, 54]	Plain [103], plating [102], rib [54]	• GF = 40.5 [103] • GF = 3 - 18 [102] • GF = 8.47 [54]	[103, 102, 54]
Piezoresistive strain sensor	Gesture recognition	Silver-coated yarn	Intarsia	• GF = 88	[104]
Piezoresistive strain sensor	Physiological sensing	Stainless steel, carbon-coated lycra [90], silver, nylon [101]	Plain [90, 101]	• GF (coursewise) = 32, GF (walewise) = 305 [90] • GF = 2.328 - 3.576 depending on different sensor designs [101]	[90, 101]
Capacitive strain sensor	Activity monitoring	Silver-coated yarn	Interlock	• GF = -0.68	[107]
Piezoelectric strain sensor	Activity monitoring	BT/PVDF [111], PVDF multifilament [112]	Tubular [58], spacer [112]	• Force sensitivity ∼ 10 V/N [111] • Force sensitivity ∼ 1.4 V/N [112]	[111, 112]
Piezoelectric strain sensor	Physiological monitoring	PVDF, carbon-coated nylon	Interlock	• Able to measure respiratory and heart beat rate under static and dynamic conditions (e.g. during sitting, HR = 1.47 Hz, Respiration rate = 0.2 Hz)	[91]

Table 3: Summary of knittable e-textiles for pressure sensing.

Type	Application	Materials	Knitting structure	Performance	Ref.
Pressure Sensing					
Piezoresistive pressure sensor	Activity monitoring	Silver-coated yarn [114], carbon-coated copper wire [113]	Spacer [114], Interlock [113]	• Normalized Conductivity under 20N: baseline = 10, stitch 32/22 = 7.2, spacing 2 = 2.125 [114] • Normalized Conductivity under 3.2N: knit = 1.25, front-miss = 1.5, tuck = 1. [113]	[114, 113]
	Gesture recognition	Graphite/copper-coated stainless steel fiber [51], Polyester knit fabric with polypyrrole[55]	Inlay [51], Interlock [55]	• Force-resistance sensitivity of 3.15 per fiber [51] • Force-resistance sensitivity of 58.7 Ω/N under 100N load, 39.4 Ω/N under 500 N load. [55]	[51, 55]
Capacitive pressure sensor	Activity monitoring	Silver-coated yarn [58, 115] Copper wire [116], Microporous knitted conductive fabric[106]	Spacer [58, 115, 116], Plain [106]	• At 20 MHz, capacitance of 13.9pF [58]. • At 1 kHz, most sensitive sensor had capacitance range of 1.9 pF to 5.2 pF, under 15 kPa [115]. • At 50 Hz, most sensitive sensor had capacitance range of 1.8 pF to 3.5 pF under 100 kPa [116]. • At 50 Hz, sensors had a normalized capacitance of .5, 1, and 1.5 with 25, 50, and 100 kPa of applied pressure respectively [106].	[58, 115, 116, 106]
Triboelectric pressure sensor	Physiological sensing	Stainless steel fiber	Interlock	• Pressure sensitivity of 7.84 mV Pa^{-1} and response time of 20 ms	[117]
Piezoelectric pressure sensor	Physiological monitoring	Silver-coated nylon[110] PVDF [118]	Plain [110]	• Voltage sensitivity of 0.1186 V/N (6.91 cm^2 sample) [110] • Voltage sensitivity of up to .34 V/N (20 cm^2 sample) [118]	[110, 118]

Table 4: Summary of knittable e-textiles for electrophysiology, environmental, and chemical sensing.

Type	Application	Materials	Knitting structure	Performance	Ref.
Electrophysiological Sensing					
Pneumography sensor	Physiological sensing	Silver-coated yarn	Intarsia	• Impedance measurements with dynamic range of 6.5 to 7.2	[220]
ECG sensor	Physiological sensing	Carbon monofilament	Plain	• Average signal to noise ratio (SNR) of 18.32	[124]
EIT sensor	Physiological sensing, gesture recognition	Stainless steel spun yarn	Intarsia	• 2.3 MΩ and 50 kΩ resistance in coursewise and walewise direction • Measurable impedance changes between 6 finger gestures • 12 different detectable on-body locations and configurations	[126]
EEG sensor	Physiological sensing	Copper yarn	Intarsia	• Impedance range of 14 kΩ to 2 kΩ (forehead), and 88 kΩ to 7 kΩ (hairy) between 1 and 10 kHz • Between 79.8 to 96.3 % average Pearson correlation to conventional EEG cap	[127]
EMG sensor	Gesture recognition	Silver-coated yarn	Intarsia	• SNR of 17.91 (compared to 13.3 for disposable electrodes) • Impedance of 376.7 Ω (compared to 201.2 for disposable elctrodes), under a input frequency of 20 Hz • 93.2% accuracy to detect 6 different hand gestures	[128]
Environmental and Chemical Sensing					
Electrochemical sensor	Physiological sensing	Stainless steel fiber, silver-coated yarn	Tubular	• Anodic and cathodic peaks observed at 238 mV and -42 mV with a peak separation of 270 mV when measuring 10 nM potassium ferricyanide in 10 mM NaCl	[139]
Temperature sensor	Physiological sensing	Gold-coated yarn [136], copper [137], nickel, tungsten [138]	Tubular [136], inlay [138]	• Sensitivity of $\sim$ 4.509 $\Omega/^{\circ}$C[136] • Sensitivity of 2.449 $\Omega/^{\circ}$C [138].	[136, 138]
Sweat and humidity sensor	Physiological sensing	Silver-coated yarn	Intarsia	• Resistance changed when treated with: water (+9.9%), acidic sweat (+2.5%), alkaline sweat (-3.8%), and saline solution (-6.8%).	[135]

Table 5: Summary of knittable e-textiles for actuation and computation.

Type	Application	Materials	Knitting structure	Performance	Ref.
Actuation					
Thermal actuation	Interactive wearables	Liquid crystal elastomers	Plain	• Actuation force: ~ 0.045–0.13 N (fiber diameter 0.5–1 mm) • Cycling frequency: ~ 6.66–2.86 cHz	[150]
Pneumatic actuation	Interactive wearables	Silver-coated yarn / acrylic yarn	Jacquard, plating	• Inflation pressure: up to 150 kPa • Graspable object diameter: ~ 3 cm • Payload capacity: ~ 125 g	[152, 258, 286]
Cable-driven actuation	Interactive wearable	Elastic yarn	Inlay	• Actuation force: 100–300 g • Output torque: 190–570 $\mathrm{g \cdot cm}$ (2.6–7.9 $\mathrm{oz \cdot in}$)	[42, 31, 50]
Magnetic actuation	Interactive wearables	Neodymium fiber	Jacquard	• Force transmission: up to 40 N • Control bandwidth: 14.5 Hz	[194, 93, 196]
Computation					
Fiber-integrated chips	Interactive wearables	Flexible PCB	Inlay	• IC embedding width: ~ 2 mm	[166]
Multifunctional fibers	Interactive wearables	Electroluminescent fiber	Plain	• Relative permittivity: $\varepsilon \approx 78$ • Electrical conductivity: $\sigma \approx 0.6\,\mathrm{S\,m^{-1}}$	[167]
Chip-embedded textiles	Physiological sensing (multi-point sensing)	TPU shell / polymer / ICs	Inlay	• Sensing nodes: 30 nodes over 1500 $\mathrm{cm^2}$ • Strain tolerance: 30% • Mechanical durability: 1000 cycles • Temperature accuracy: 0.1°C	[71]

Table 6: Summary of knittable e-textiles for communication and powering modalities.

Type	**Application**	**Materials**	**Knitting structure**	**Performance**	**Ref.**
Communication					
UHF RFID tag	Physiological sensing (battery-free monitoring)	Silver-coated yarn	Intarsia	• 77 % classification for breathing and non-breathing patterns. • Wireless backscatter at 870–915 MHz with 0.8 dBi.	[179]
Metamaterial antenna	Interactive wearables	Silver-coated yarn	Intasia [180], Jacquard [46]	• Frequency selective surfaces around 8 GHz [180]. • Metalens at 5.4 GHz with 15.30 dB gain [46]. • Vortex generator at 4.1–5.8 GHz [46].	[180, 46]
NFC transmitter (meander coil)	Physiological sensing (body-scale sensing)	Silver-coated yarn	Tubular	• Readout of battery-free NFC sensor tags at 13.56 MHz band. • Wide coverage around the body.	[31, 50]
Powering					
TENG	Interactive wearables (self-powered wearables)	+: PA66, −: PTFE [194] +: Ag, −: PTFE [93] +: PA66, −: Cotton [196]	Interlock [194, 93, 196]	• 7.5 mW/m^2 under compress, 1.5 mW/m^2 under stretch[194]. • 23.50 V and 1.05 µA under stretch[93]. • 3.4 mW/m^2 under compress [196].	[194, 93, 196]
PENG (yarn)	Activity recognition	PVDF/$BaTiO_3$	Circular	87 µW/cm^3.	[111]
PENG (fabric)	Activity recognition	PVDF monofilament	Spacer	11–51 mW/m^2.	[53]
TEG	Physiological sensing	Carbon nanotube yarn	Spacer	51.5 mW/m^2 at 47.5 K temperature gradient.	[200]
Supercapacitor	Interactive wearables	MXene yarn	Intarsia [206] Spacer [207]	• 707 mF/cm^2 [206]. • 415 mF/cm^2, 97 % retention after 1000 cycles [207].	[206, 207]
Wireless inductive charger (spiral coil)	Interactive wearables (continuous operation)	Copper wire	Tubular	• 30 % AC-to-AC efficiency at 0.6 cm distance • Narrow coverage around wrist and neck.	[188]
Wireless inductive charger (meander coil)	Interactive wearables (body-scale operation)	Liquid metal tube (eGaIn)	Plate	• 20 % AC-to-AC efficiency at 1 cm distance [47]. • Wide coverage around the body. • 2.5 W safe power delivery within SAR limits. • Machine-washable over 100 cycles [212].	[47, 212]
Body-coupled charger	Physiological intervention (muscle stimulation)	Silver-coated yarn	Jacquard	• 10–100 mV/mm electric field generated to activate muscle fibers. • Full-body coverage. • Machine-washable over 20 cycles.	[213]

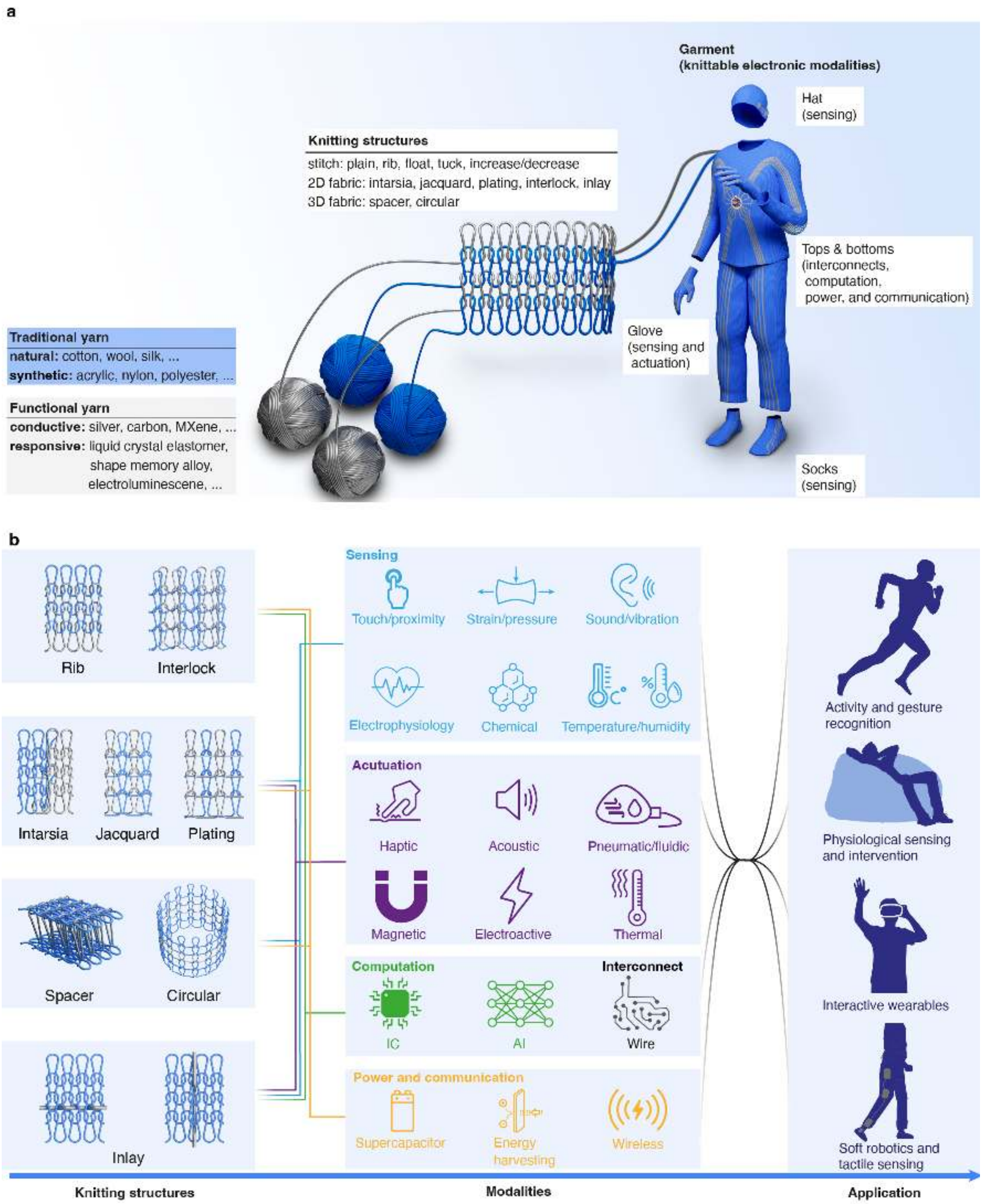

Figure 1: **a:** Schematic illustration of knittable electronic textiles (e-textiles). Functional yarns are knitted into everyday garments using loop structures. Their mechanical flexibility and high surface area can facilitate intelligent soft wearables. **b:** Fibers and yarns, knitting structures, modalities, and applications of knittable e-textiles. Icons in Modalities and Application were obtained from istockphoto.com under standard license.

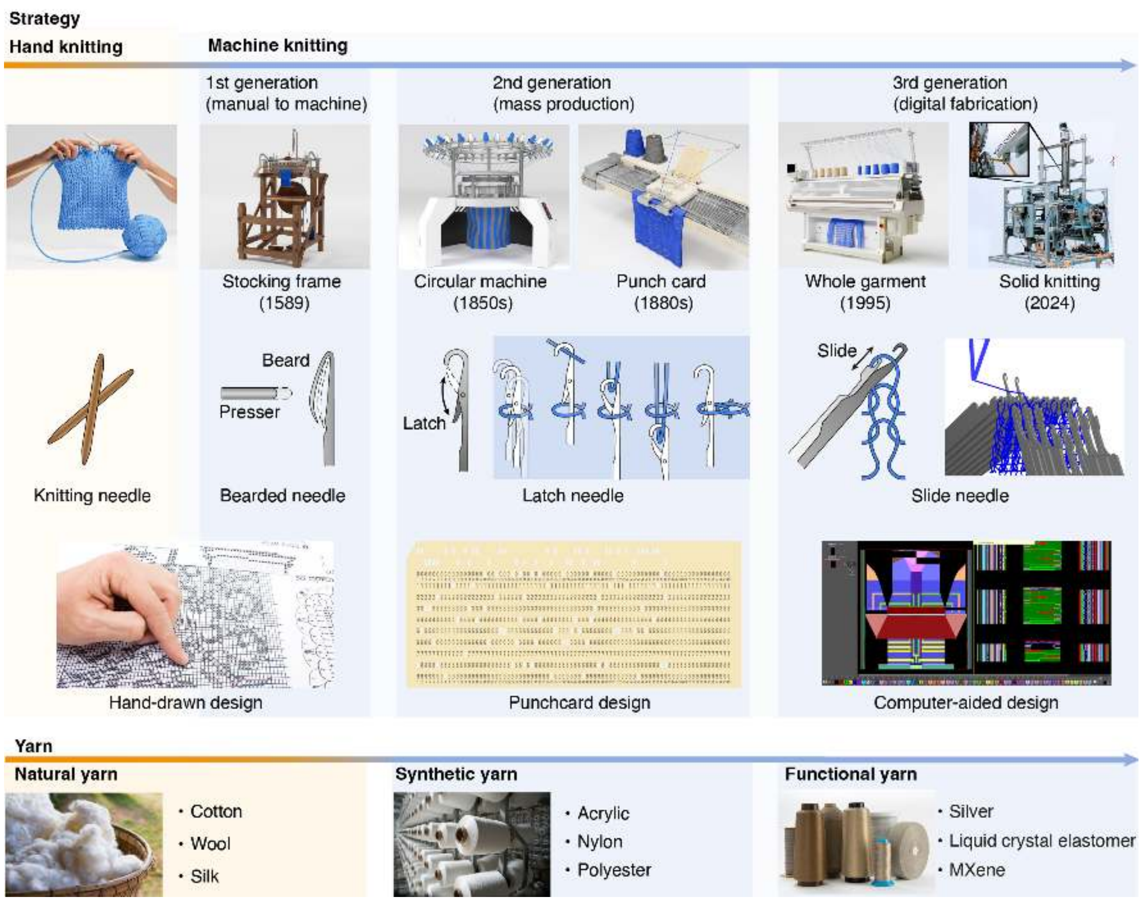

Figure 2: Technological timeline in knitting technologies and fiber development. (solid knit, right top) reproduced from ACM [21], under CC BY 4.0 license.

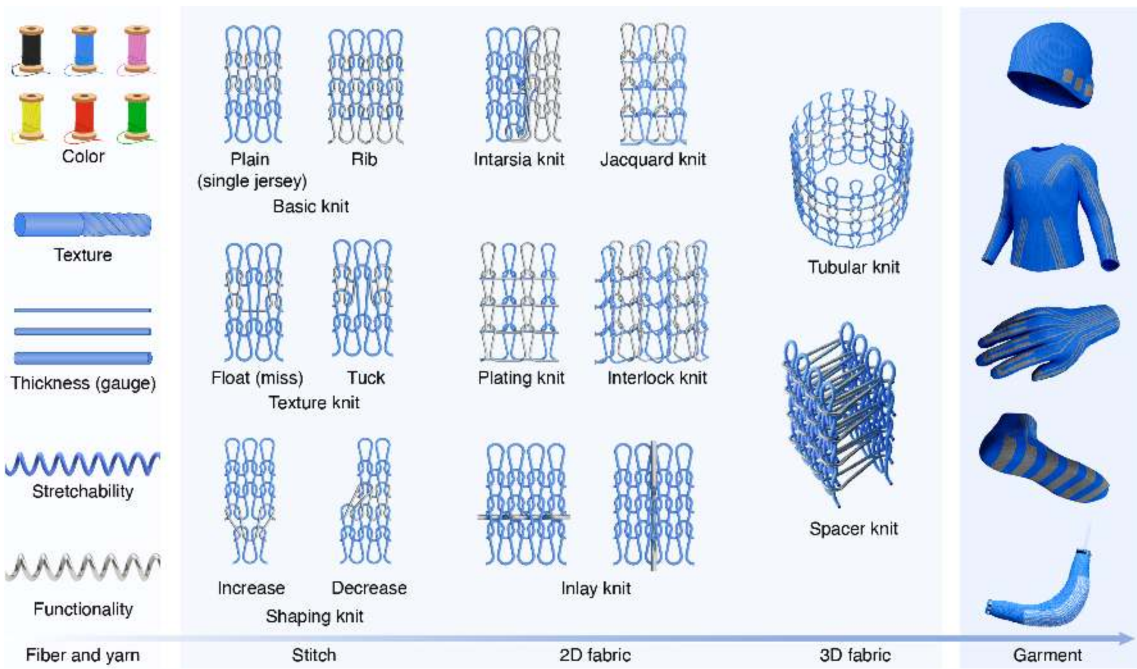

Figure 3: Hierarchical structural design of knittable e-textiles composed of five levels. Yarn level: modulation of physical and functional properties. Stitch level: fundamental loop structures and shaping techniques. Fabric level: 2D and 3D fabrics through intarsia, jacquard, plating, interlock, inlay, circular, and spacer knitting. Garment level: diverse wearable and soft-robotic smart garments enabled by digital knitting.

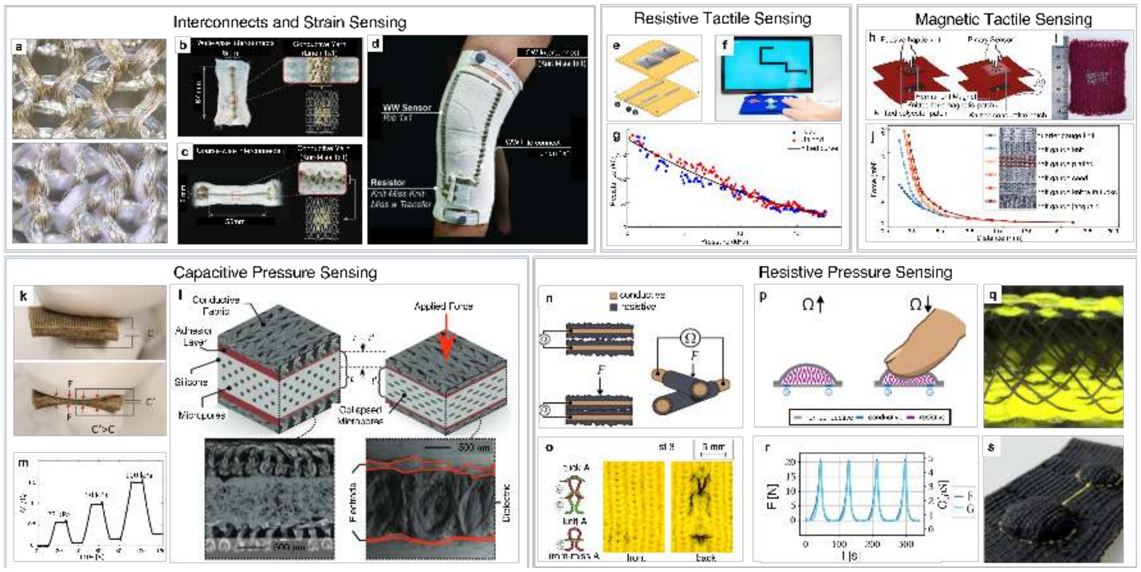

Figure 4: Examples of knittable interconnects and sensors utilizing capacitive and piezoresistive capabilities. **a:** Weft knitted capacitive pressure sensors with conductive yarn interconnects. Reproduced with permission [58]. Copyright 2018, Taylor & Francis. **b:** Close up of walewise interconnect made with a linen 1x1 stitch. **c:** Close up of course-wise interconnect made with knit-miss 1x1 stitch. Reproduced with permission [54]. Copyright 2023, John Wiley & Sons. **d:** Integration of coursewise and walewise interconnects and rib-knit strain sensor knitted into knee joint monitoring sleeve. Reproduced with permission [105]. Copyright 2023, IEEE. **e-g:** Piezoresistive tactile sensing for a game controller. Reproduced from ACM [84], 2021 under CC BY 4.0 license. **e:** Assembly schematic of piezoresistive tactile sensor **f:** Usage of the game controller for snake game. **g:** Sensor data based on touch pressure and resistance change. **h-j:** Magnetic haptic touch sensor. Reproduced from ACM [86], 2023 under CC BY 4.0 license. **h:** Schematic for magnetic passive haptic touch unit and binary touch sensor. **i:** Example swatch of ferromagnetic patch knitted into non-conductive fabric. **j:** Sensor data of magnetic force vs distance for different knit types. **k-m:** Capacitive pressure sensor. Reproduced with permission [106]. Copyright 2018, John Wiley & Sons. **k:** Prototype of knitted sensor under pressure. **l:** Schematic of sensor cross section showing collapsed micropores of dielectric elastomer (top) and SEM images of sensor (bottom) **m:** Sensor capacitance response under applied pressure. **n-o:** Piezoresistive touch sensor made with intermeshed loops. Reproduced from ACM [113], 2024 under CC BY 4.0 license. **n:** Schematic of force sensitive resistor (FSR), where external stress varies the surface contact and alters conductivity. **o:** Implementation of FSR using two types of stitches: knit and front miss. **p-s:** Piezoresistive touch sensor made with resistive filler material. Reproduced from ACM [114], 2022 under CC BY 4.0 license. **p:** Schematic of touch sensor cross section, highlighting predicted resistance changes during touch, as well as nonconductive out layers, resistive filler, and conductive electrodes. **q:** Cross-sectional image of touch sensor with resistive filler. **r:** Force and conductivity measurements align during touch sensing. **s:** Sensor implementation in two buttons.

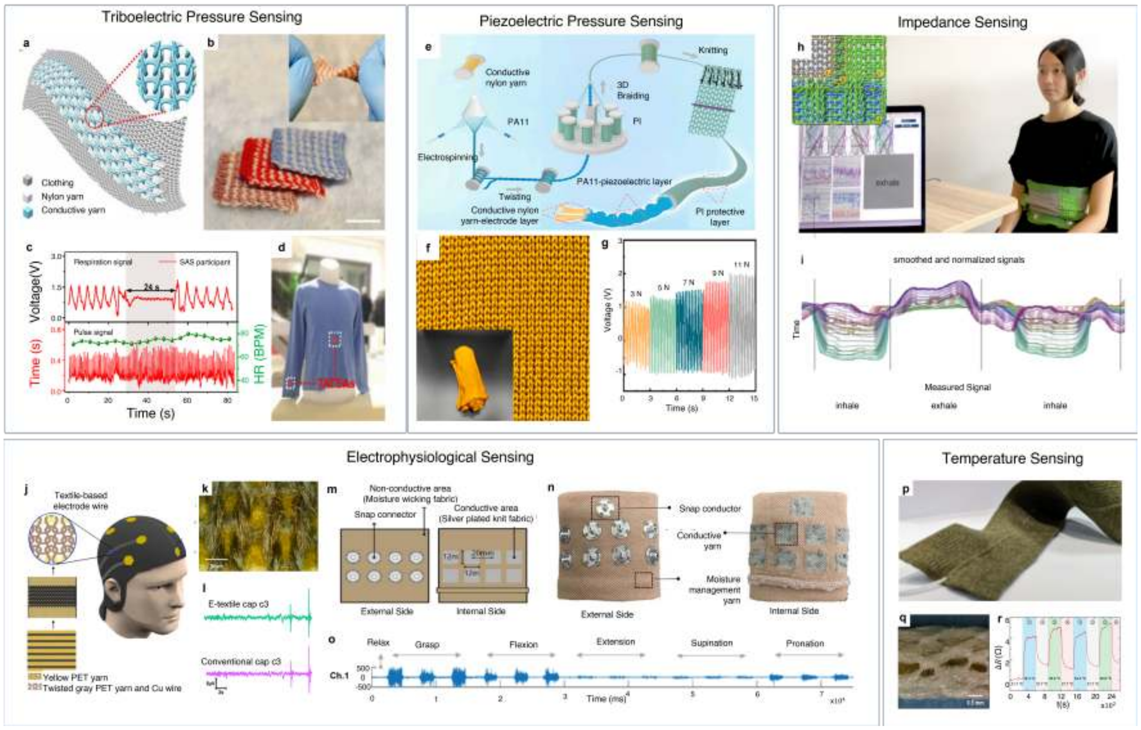

Figure 5: Examples of knittable strain and tactile pressure sensors. **a-d**: Triboelectric strain sensor for wearable health monitoring. Reproduced with permission [117]. Copyright 2020, AAAS. **a:** Sensor schematic with areas of nylon (non-conductive) and conductive yarn. **b:** The fabricated sensor prototype remains soft and flexible after fabrication. **c:** When integrated, it can sense respiration and pulse in real time based on voltage changes, and **d:** seamlessly integrate into a shirt. **e-g**: Piezoelectric pressure sensor made from twisting and braiding conductive and piezoelectric fibers. Reproduced with permission [110]. Copyright 2025, Elsevier. **e:** Fabrication schematic of piezoelectric yarn sensor **f:** Fabric made of knitted piezoelectric yarns. **g:** Voltage response with increasing pressures from 3 N to 11 N at a frequency of 4 Hz. **h-i:** Knitted garment for health and gesture monitoring. Reproduced from ACM [126], 2022 under CC BY 4.0 license. **h:** When the user is wearing this garment, breathing can be detected through EIT enabled via impedance sensing. **i:** Respiration rate monitoring around the waist. **j-l:** Knitted EEG cap with knitted electrode wiring. Reproduced with permission [127]. Copyright 2025, Elsevier. **j:** Visualization of knitted e-textile EEG cap. **k:** close-up image of knitted structure of electrode. **l:** Sensor data showing the cap is comparable to traditional caps. **m-o:** Knitted armband with electrodes for surface EMG signal detection. Reproduced with permission [128]. Copyright 2018, IEEE. **m:** Schematic of arm band, with conductive areas knitted with intarsia. **n:** Prototype of an arm band. **o:** One of eight sEMG channels able to detect signals during various hand gestures. **p-r:** Temperature sensing arm band using an embedded RTD sensor. Reproduced from MDPI [136], 2022 under CC BY 4.0 license. **p:** garment prototype with sensor embedded in knit fabric. **q:** A knitted coating was applied over the temperature sensor. **r:** Sensor data for temperature change was collected for the user at rest, during and after exercise.

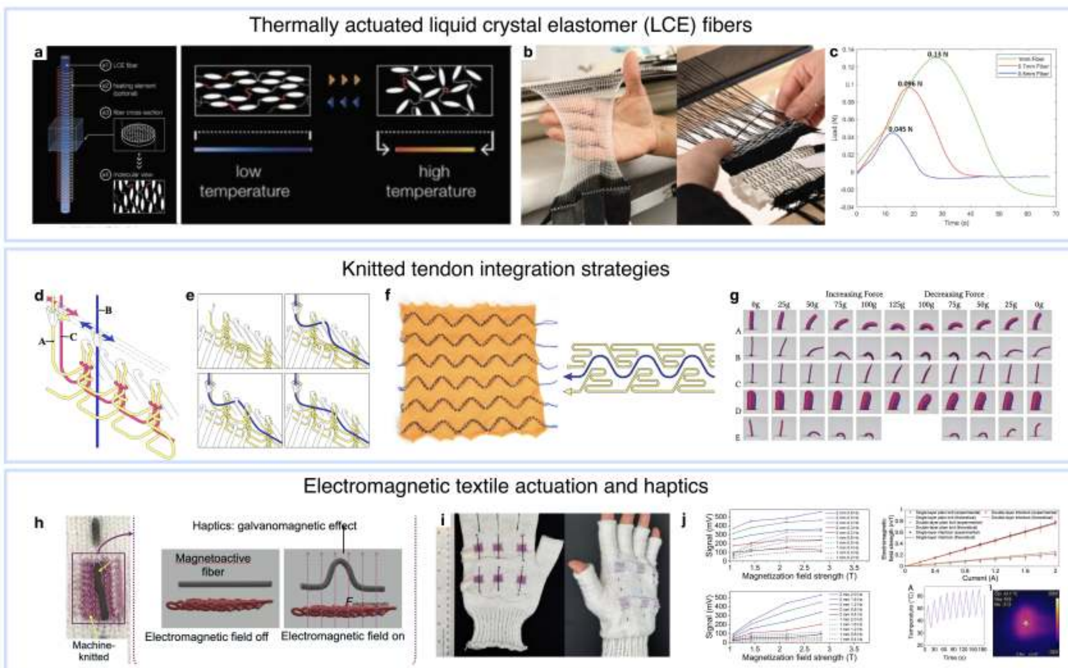

Figure 6: Examples of knittable actuation techniques. **a–c:** Thermally actuated liquid crystal elastomer (LCE) fibers. Reproduced from ACM [150], 2023 under CC BY 4.0 license. **a:** Schematic of an LCE fiber actuator with an embedded heating element, illustrating molecular alignment changes under temperature variation. **b:** Fabrication pipeline from individual actuating fibers to integrated 4D knitted fabrics. **c:** Peak tensile loads generated during heating–cooling cycles for LCE fibers of different diameters (1.0 mm, 0.7 mm, and 0.5 mm). **d–f:** Knitted tendon integration strategies. Reproduced from ACM [42], 2019 under CC BY 4.0 license. **d:** Tangling technique for embedding vertical tendons, where carriers move along dedicated rails to avoid interference during directional transitions. **e:** Inlay technique for embedding horizontal tendons within knit structures. **f:** Diagram illustrating the resulting knit row configurations and tendon routing. **g:** Mechanical response comparison of fabrics using different stuffing materials under increasing and decreasing applied forces. **h–j:** MagTex electromagnetic textile actuation and haptics. Reproduced from ACM [78], 2025 under CC BY 4.0 license. **h:** Working principle of the MagTex haptic mechanism, where an alternating current induces vibration through galvanomagnetic and electromagnetic induction effects. **i:** Smart glove prototype incorporating six distributed MagTex actuator units. **j:** Characterization of the knitted electromagnet, showing signal response as a function of thermal variation and applied electromagnetic field strength.

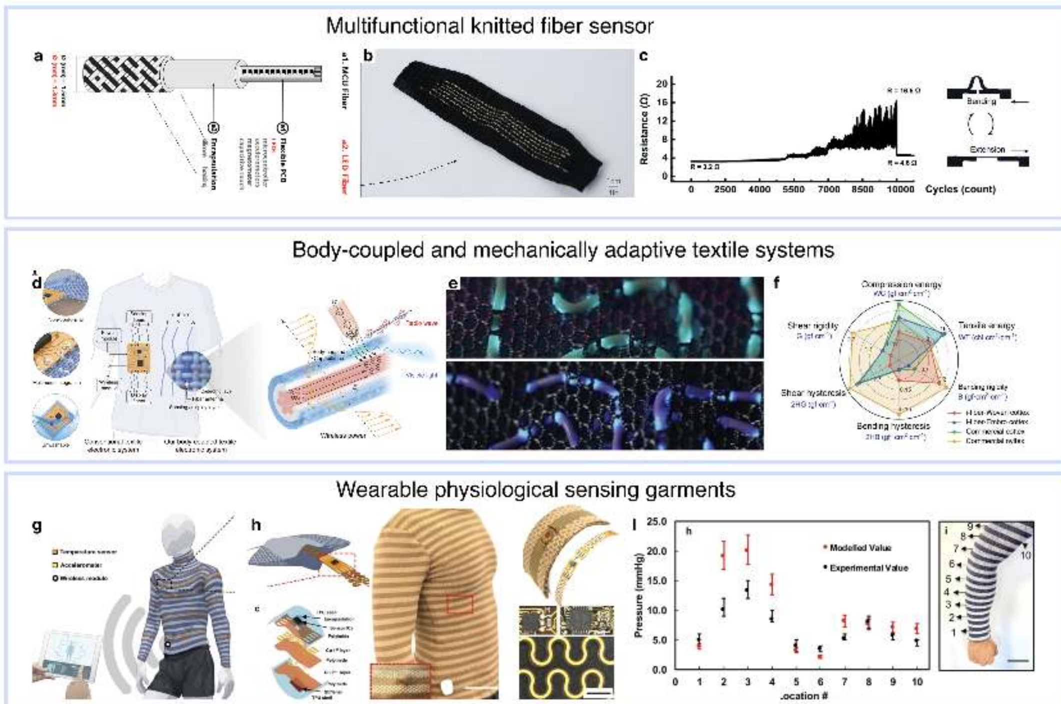

Figure 7: Examples of textile-based sensing and integrated wearable electronic systems. Multifunctional knitted fiber sensor. **a-c:** Multifunctional knitted fiber sensor structure and its resistive response for strain. Reproduced from ACM [166], 2025 under CC BY 4.0 license. **a:** Schematic of a knitted fiber integrating an MCU fiber and LED fiber, encapsulated with flexible polymer layers and connected to a flexible PCB for signal processing. **b:** Photograph of the fabricated knitted sensor embedded within a textile substrate. **c:** Electrical resistance response under repeated bending and extension cycles, demonstrating mechanical durability over 10,000 cycles. **d–f:** Body-coupled and mechanically adaptive textile systems. Reproduced with permission [167]. Copyright 2024, AAAS. **d:** System overview comparing conventional textile electronics with a body-coupled textile electronic system that integrates sensing fibers, wireless power transfer, and display fibers. **e:** Close-up optical images of the textile structure showing embedded functional elements under illumination. **f:** Radar plot comparing mechanical properties, including compression energy, tensile energy, bending rigidity, and hysteresis across i-fiber woven textiles, commercial cortex fabrics, and conventional nyltex. **g–i:** Wearable physiological sensing garments. Reproduced from Springer Nature [287], 2020 under CC BY 4.0 license.**g:** Smart garment integrating temperature sensors, accelerometers, and wireless modules distributed across the textile for continuous monitoring. **h:** Layered structure and fabrication details of a stretchable sensor module embedded within knit fabrics, along with garment-level integration examples. **i:** Validation of pressure sensing performance, showing modeled versus experimental pressure measurements across multiple sensing locations on the garment.

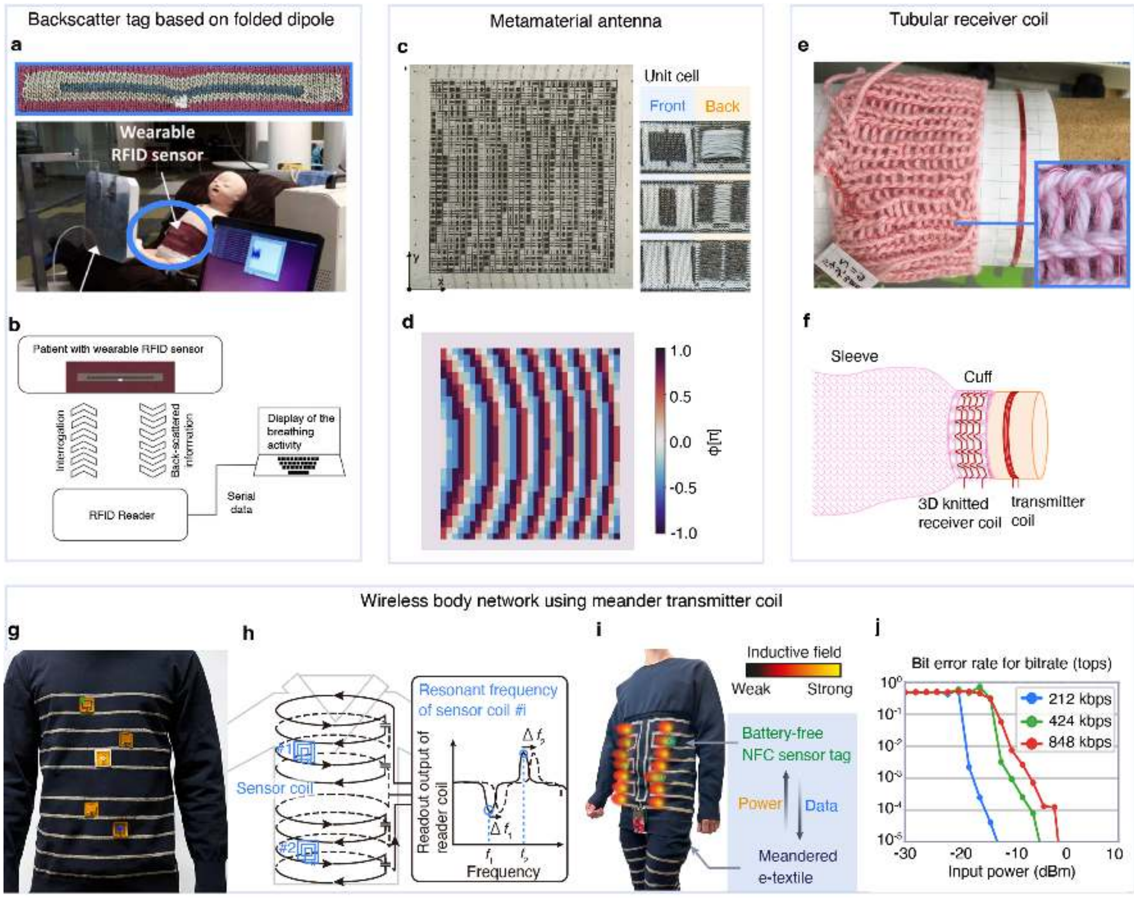

Figure 8: Examples of knittable communication-enabled e-textiles. **a-b:** Knitted RFID tag created by intarsia knitting of conductive yarns. Reproduced with permission [179]. Copyright 2016, IEEE. **a:** System overview of wearable RFID sensor. **b:** Backscatter communication between the knittable RFID tags and an external wireless reader. **c-d:** Knittable matamaterial antenna created by double-layered jacquard knitting of conductive yarn and dielectric nylon yarn. Reproduced with permission [46]. Copyright 2024, John Wiley & Sons. **c:** Photograph of the knittable metamaterial antenna and **d:** its phased modulation pattern. **e-f:** Knittable 3D spiral receiver (RX) coil. Reproduced with permission [188]. Copyright 2021, Elsevier. **e:** Photograph of the knittable RX spiral coil and **f:** schematics around the wrist. **g-h:** Knittable 3D meander coil by intarsia knitting. Reproduced from ACM [31], 2021 under CC BY 4.0 license. **g:** Photograph of the knittable meander coil. **h:** Wireless interrogation of the meander coil for battery-free on-body resonant sensor coils. **i-j:** NFC-based knittable meandered e-textiles. Reproduced with permission from Ryo Takahashi [50].**i:** Photograph of the NFC-based knittable meandered e-textiles. **j:** NFC performance of the meandered e-textiles for different NFC data rates.

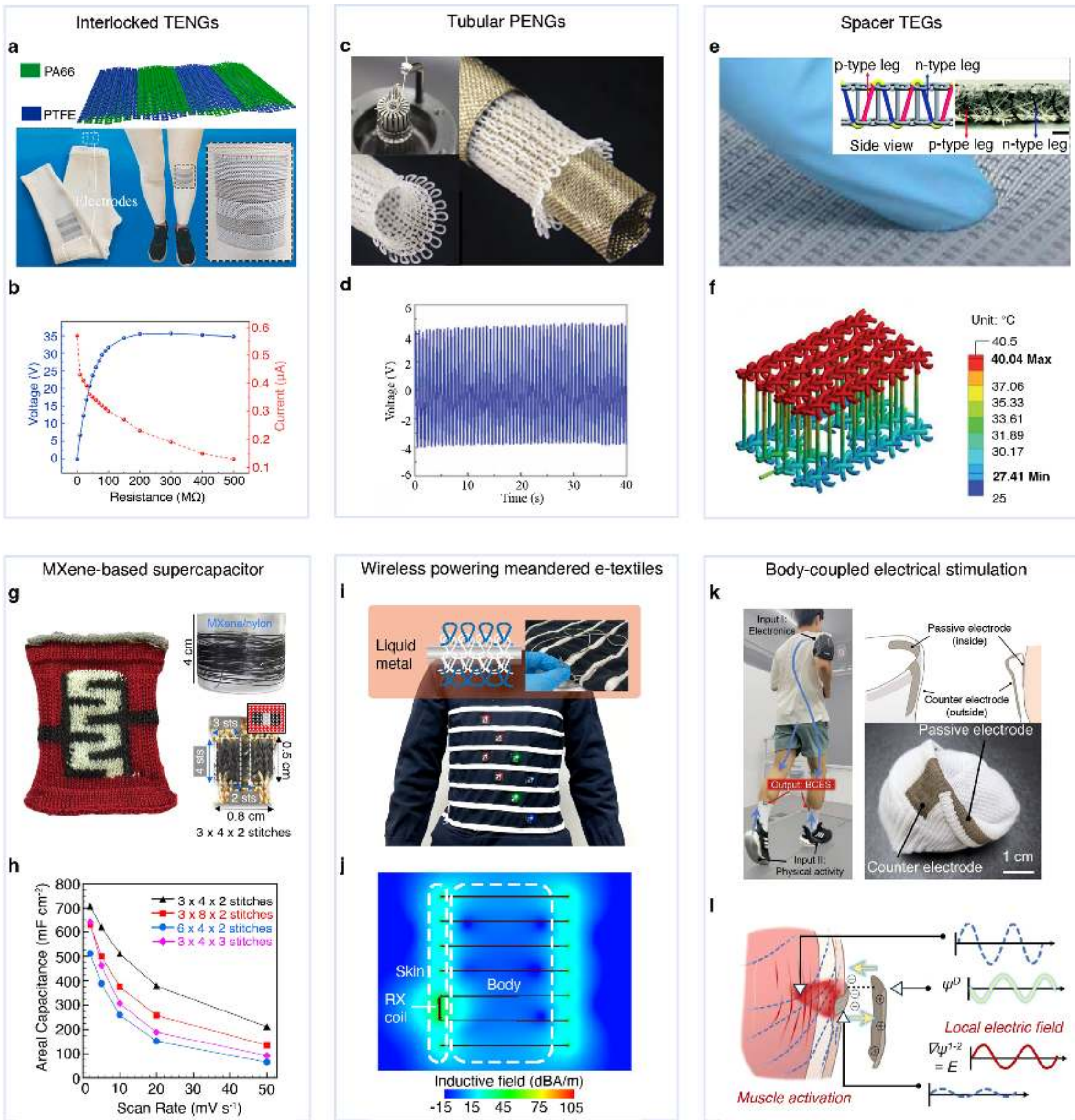

Figure 9: Examples of knittable powering e-textiles. **a-b:** Knittable triboelectric nanogenerators (TENGs) by interlock knitting of PA66 and PTFE yarns. Reproduced with permission [194]. Copyright 2020, Elsevier. **a:** Prototype photograph of the knittable TENGs. **b:** Electrical output performance of the TENG textile showing voltage and current relative to load resistance. **c-d:** Knittable piezoelectric nanogenerators (PENGs) with a tubular knit structure. Reproduced from John Wiley & Sons [111], 2020, under CC BY 4.0 license. **c:** Prototype photograph of the knittable PENGs. **d:** Voltage output of the PENG textile over time under mechanical deformation. **e-f:** Knittable thermoelectric generator (TEG) based on a 3D spacer knit structure, where vertical carbon-nanotube yarns serve as pillars to maintain a temperature gradient. Reproduced with permission [194]. Copyright 2020, The Royal Society of Chemistry.**e:** Prototype photograph of the knittable TEG. **f:** Thermal simulation across the textile. **g-h:** knittable supercapacitor fabricated via intarsia knitting, interlacing MXene-coated cotton yarns into a dense interlock rib structure to create 2D planar electrodes. Reproduced with permission [206]. Copyright 2020, Elsevier. **g:** Prototype photograph of the knittable supercapacitor. **h:** Areal capacitance performance for scan rates. **i-j:** Knittable meander coil integrated into a garment by inserting a liquid-metal-filled tube in a plating-knitted tube holder. Reproduced from ACM [47], 2022, under CC BY 4.0 license.**i:** Prototype photograph of the knittable meander coil for Watt-class wireless powering. **j:** Simulation of the inductive field generation around the meander coil. **k-l:** Knittable socks with two pairs of electrodes for body-coupled electrical stimulation. Reproduced from ACM [213], 2024, under CC BY 4.0 license. **k:** Prototype photograph of the knittable socks for body-coupled electrical stimulation. **l:** Schematic of wireless electrical stimulation of muscle via the local electric field generated between the electrodes.

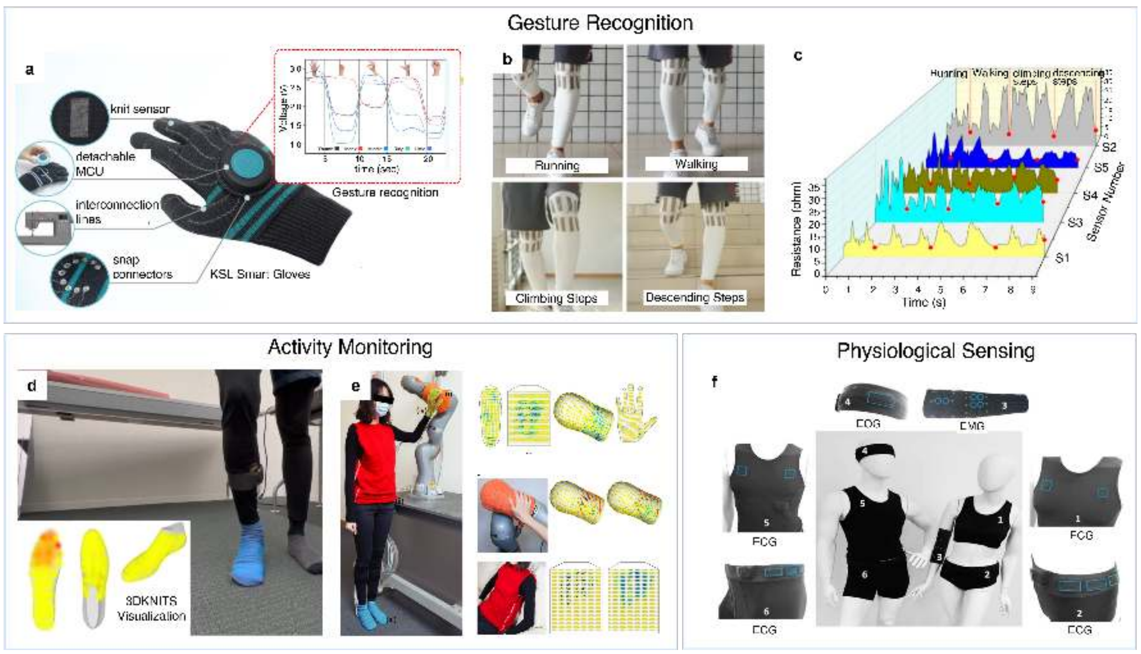

Figure 10: Examples of knittable e-textiles applications for gesture recognition, activity monitoring, and physiological sensing. **a:** A Korean Sign Language glove that can recognize 8 different KSL gestures. Reproduced from MDPI [104], 2025 under CC BY 4.0 license. **b:** Knitted sensors on sweatpants that enable detection of lower body movement type, such as walking, running, ascending or descending stairs. Reproduced from MDPI [215], 2019 under CC BY 4.0 license. **c:** Distinct signals from each movement type for categorization. **d:** Knitted shoe able to detect pressure during activity. Reproduced with permission [55]. Copyright 2022, IEEE. **e:** Full body garments for human-environment and human-robot sensing. Reproduced with permission [51]. Copyright 2021, Springer Nature. **f:** Garments enabling EOG, ECG, and EMG signal detection. Reproduced with permission [124]. Copyright 2022, John Wiley & Sons.

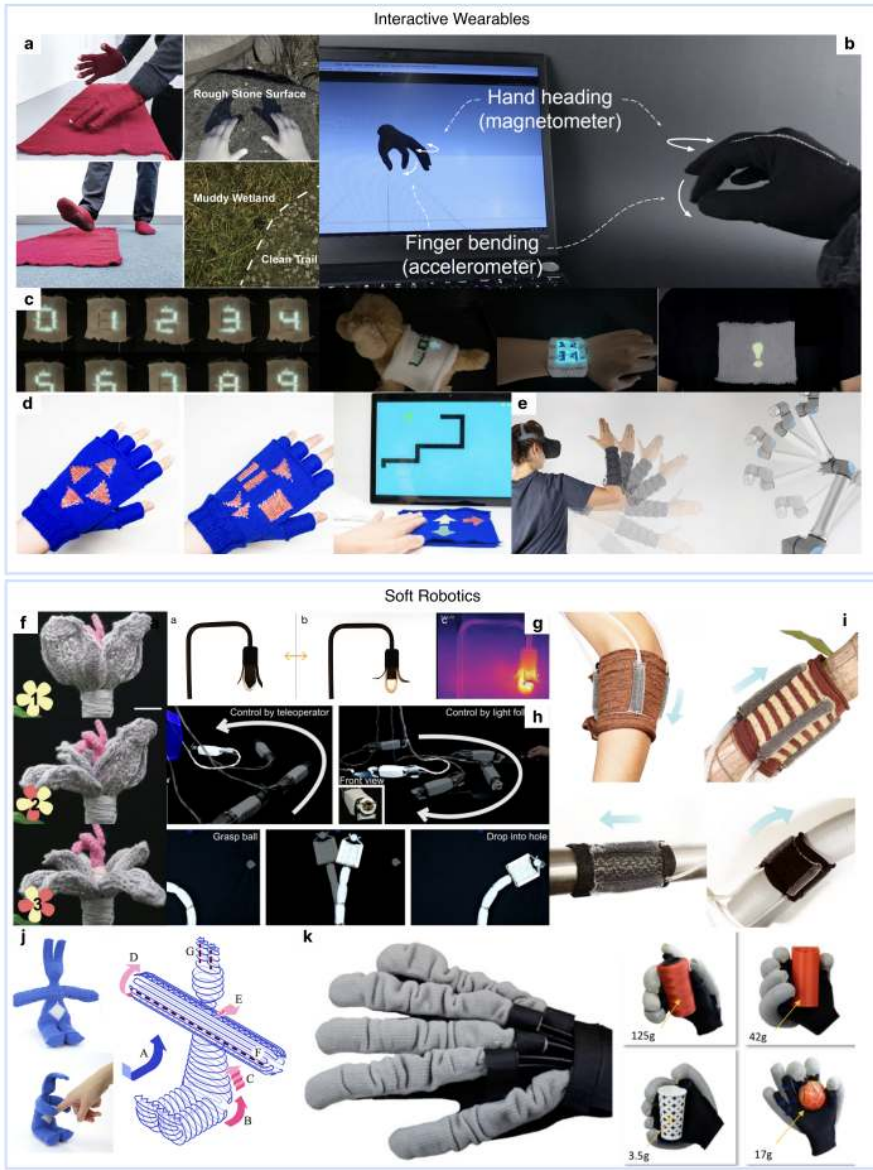

Figure 11: **a:** Knittable interactive surfaces enabling integrated sensing and haptic feedback for virtual reality interaction. Reproduced from ACM [288], 2023 under CC BY 4.0 license. **b:** Glove-based input system capturing hand orientation and finger bending using embedded inertial sensors. Reproduced from ACM [166], 2025 under CC BY 4.0 license. **c:** Fabric-integrated textile displays providing dynamic visual feedback directly on garments. Reproduced from ACM [162], 2025 under CC BY 4.0 license. **d:** Knitted glove interface with conductive patterns supporting directional and gesture-based input. Reproduced from ACM [84], 2021 under CC BY 4.0 license.**e:** Wearable textile controller enabling continuous arm and hand interaction for robotic control. Reproduced with permission [160]. Copyright 2024, AAAS. **f:** The textile-based actuator morphs through the activation of a shape-memory alloy. Reproduced with permission [149]. Copyright 2027, John Wiley and Sons . **g:** A morphing lamp cover using textile actuators that respond to thermal stimuli. Reproduced from ACM [150], 2023 under CC BY 4.0 license. **h:** Wearable soft robotic sleeve providing assistive arm bending via fabric-based actuation. Reproduced with permission [120]. Copyright 2018, AAAS. **i:** Textile reinforced soft actuators enabling controlled deformation and directional motion for health and assistive applications. Reproduced from ACM [152], 2022 under CC BY 4.0 license. **j:** Schematic and prototype of a textile actuator illustrating stitch- and fiber-defined motion behaviors. Reproduced from ACM [42], 2019 under CC BY 4.0 license. **k:** Soft robotic glove with integrated pneumatic textile actuators enabling adaptive grasping of objects with diverse shapes and weights. Reproduced from MDPI [155], 2021 under CC BY 4.0 license.

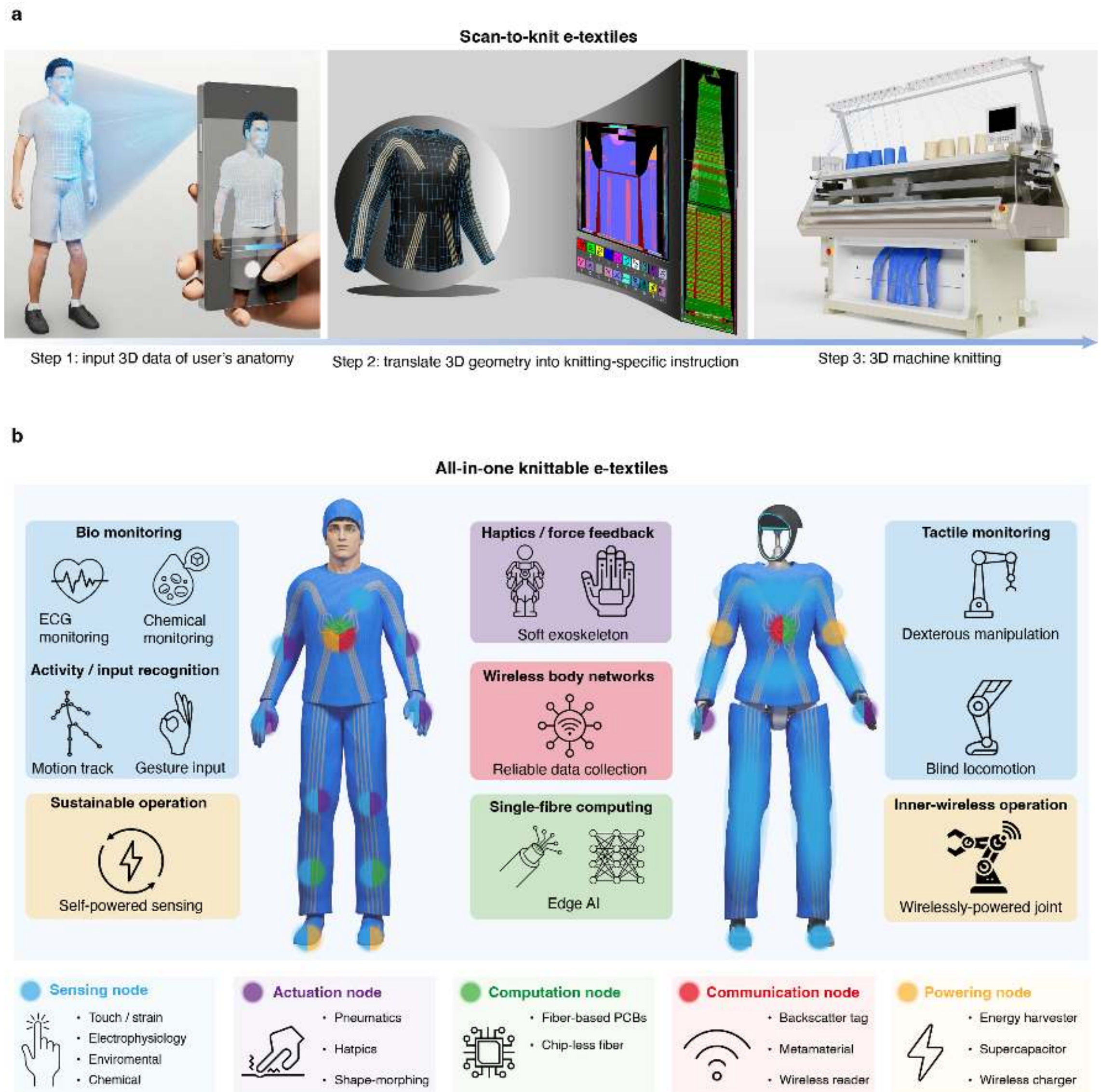

Figure 12: Outlook of knittable e-textiles. **a:** scan-to-knit e-textiles, mainly comprising three steps: 3D body scanning of the user, computational design for mapping functional patterns onto the garment geometry, and automated fabrication using industrial 3D knitting machines. **b:** all-in-one knittable e-textiles. The integration of sensing, actuation, computation, communication, and powering nodes enables diverse applications ranging from bio-monitoring and haptic feedback to edge AI and a self-powered wearable ecosystem.