

AI-Enabled Smart Clothing for Continuous Health Monitoring: A Review of Materials, Sensors, Data Analytics, and Clinical Applications

Mehak Kaushik¹, Dr. Bindu Thakral²

^{1,2}School of Engineering & Technology, Sushant University, Gurugram, India

¹mehak.250btccse073@sushantuniversity.edu.in, ²binduthakral@sushantuniversity.edu.in

Abstract—Smart clothing, formed by the convergence of conductive textiles, electrochemical and physical sensors, and artificial intelligence (AI), is repositioning everyday garments as continuous, non-invasive health-monitoring platforms. This paper reviews the state of AI-enabled smart clothing, covering the conductive and functional materials that make garments sensor-ready, the classes of electrochemical and biophysical sensors embedded in textiles, and the machine-learning and deep-learning pipelines used to convert raw fabric-sensor streams into clinically actionable information. We synthesize evidence on applications spanning chronic-disease management, athletic performance, and, as a focused case study, stroke risk detection and post-stroke rehabilitation, where garments such as electrocardiogram (ECG)-instrumented shirts, pressure-sensing socks, and electromyography (EMG) garments complement conventional imaging by extending monitoring beyond the clinic. We further examine data-privacy, security, and ethical obligations associated with continuous physiological sensing, and outline the principal technical barriers — sensor durability, power supply, washability, and standardization — that currently limit large-scale adoption. The review concludes that, while smart clothing is not a substitute for diagnostic imaging in acute care, it is a credible complement across the prevention-to-rehabilitation continuum, and that realizing its potential will require interdisciplinary work on durable materials, energy harvesting, federated and privacy-preserving learning, and rigorously validated clinical protocols.

Index Terms—Smart clothing, wearable sensors, artificial intelligence, electrochemical sensors, conductive textiles, health monitoring, stroke rehabilitation.

I. INTRODUCTION

Clothing has historically served protective, thermal, and aesthetic functions. The convergence of textile engineering, flexible electronics, and artificial intelligence over the last decade has added a fourth function: continuous physiological sensing. Smart clothing — garments in which conductive fibers, printed electrodes, and miniaturized electronics are integrated directly into the fabric — is now capable of tracking cardiac rhythm, respiration, hydration, muscle activation, gait, and even biochemical markers in sweat, without the bulk or intrusiveness of conventional medical instrumentation [1, 2].

Two forces have driven this transition from laboratory prototype to near-market product. First, materials science has produced conductive polymers, metallic and carbon-based fibers, and stretchable encapsulation layers that preserve the flexibility, breathability, and washability expected of ordinary garments while still forming reliable electrical circuits [1]. Second, the growth of machine learning — from classical classifiers to deep sequence models — has made it possible to convert the large, noisy, multi-channel data streams produced by textile sensors into meaningful, real-time clinical or performance feedback [1]. Applications now span the full continuum of care. In general health and fitness, garments from vendors such as Hexoskin and Sensoria track heart rate, respiration, and gait for wellness and athletic optimization. In clinical contexts, ECG-instrumented shirts support arrhythmia screening, pressure-sensing socks assist diabetic-foot and gait-asymmetry monitoring, and electromyography (EMG) garments support neuromuscular rehabilitation [2]. A recent bibliometric analysis of the field confirms

this trajectory quantitatively, reporting that publication output on AI-driven wearable smart textiles has grown from roughly 80 articles in 2019 to more than 560 by mid-2025, with materials science, electronic engineering, and AI-based analytics forming the dominant interdisciplinary core [14]. A particularly instructive example is stroke care, where conventional computed tomography (CT) and magnetic resonance imaging (MRI) remain indispensable for acute diagnosis, but wearable garments are increasingly used to extend monitoring into the prevention and rehabilitation phases that imaging cannot practically cover [2].

This paper reviews AI-enabled smart clothing across four dimensions: (i) the materials and sensor technologies that make garments sensor-ready; (ii) the AI and machine-learning techniques used to process the resulting data; (iii) representative clinical and athletic applications, with stroke care used as an illustrative case study of how smart clothing complements medical imaging; and (iv) the data-privacy, ethical, and technical barriers that must be addressed before widespread clinical adoption is realistic. The remainder of the paper is organized as follows. Section II summarizes the review methodology. Section III reviews conductive textiles and embedded electrochemical sensors. Section IV discusses AI and signal-processing approaches applied to garment-generated data. Section V surveys applications in chronic-disease management, sports, and stroke care. Section VI discusses the broader implications of these findings, Section VII addresses privacy, security, and ethics, Section VIII discusses technical limitations, and Section IX outlines future directions before Section X concludes.

II. METHODOLOGY

This review synthesizes findings from the recent peer-reviewed literature on smart clothing, with two sources treated as primary anchors: a broad multidisciplinary review of AI-powered smart clothing for healthcare and fitness [1], and a narrative review focused on smart clothing and medical imaging for stroke care [2]. These were supplemented with additional peer-reviewed sources on wearable biosensors, textile electronics, and clinical validation of specific commercial garments [3, 4, 5, 6, 7, 8], identified through the reference networks of the two anchor articles. Material was organized thematically into materials and sensing, AI and signal processing, clinical and athletic applications, and privacy/ethics/limitations, with the stroke literature used specifically to illustrate how continuous wearable monitoring relates to episodic diagnostic imaging across a single disease pathway. Because this is a narrative rather than a systematic review, it does not claim exhaustive coverage; instead, it aims to give a structured, technically grounded synthesis of the state of the art and open problems in AI-enabled smart clothing.

III. MATERIALS AND SENSOR TECHNOLOGIES

A. Conductive and Functional Textiles

The electrical backbone of smart clothing is provided by conductive fibers and threads made from silver, carbon, copper, or nanocomposite materials, which are woven, knitted, embroidered, or printed onto or into fabric to form circuits capable of carrying both power and data [1]. Silver-coated fibers are widely used because they combine high conductivity with antimicrobial properties that are useful for garments in prolonged skin contact, while carbon nanotubes and graphene-based textiles offer high conductivity with lower weight and greater flexibility, which is advantageous in high-performance sport and medical garments [1]. Conductive polymers such as PEDOT and polypyrrole retain electrical performance under stretching and folding, enabling less intrusive garment designs [1].

Beyond raw conductivity, practical garments must retain flexibility, breathability, washability, and durability under the mechanical stress of daily wear. Encapsulation with hydrophobic coatings or biocompatible polymers, together with self-healing conductive pathways, has been used to preserve sensor performance across repeated wash cycles, while porous and mesh-based sensor placements preserve airflow in prolonged-wear health-monitoring garments [1]. A 2026 review of textile-integrated soft sensors emphasizes that wearability itself — comfort, conformability, and imperceptibility during long-term wear — remains a distinct engineering challenge from raw sensing accuracy, and argues that future garment design must optimize both jointly rather than treating wearability as an afterthought to sensor performance [13]. A summary of common materials, their properties, and representative use cases is given in Table 1.

B. Electrochemical and Biophysical Sensors

Electrochemical sensors convert biochemical signals into measurable electrical output, typically via potentiometric, ampero-

Table 1: Representative conductive and functional materials used in smart clothing

Material	Key property	Typical use
Silver-coated fibers	High conductivity, antimicrobial	ECG electrodes, circuit traces
Carbon nanotubes / graphene	Lightweight, high conductivity, flexible	Strain and biosensors
Conductive polymers (PEDOT, polypyrrole)	Stretchable, tunable conductivity	Flexible biosensors
Piezoelectric fibers	Converts strain to charge	Motion and energy harvesting
Phase-change materials	Thermal regulation	Adaptive thermal garments

metric, or conductometric mechanisms. In smart clothing, sweat is the dominant sensing medium: electrolytes (sodium, potassium, chloride), metabolites (lactate, glucose), and hormonal markers (cortisol) can be measured using ion-selective electrodes or enzymatic reactions built into silver/silver-chloride, gold, or graphene electrodes integrated into the fabric [1]. Non-invasive glucose sensing through sweat analysis, in particular, is being explored as an alternative to finger-prick testing for diabetes management, although enzyme stability, cross-reactivity with other sweat components, and inter-subject variability remain open problems [1].

Alongside electrochemical sensors, garments increasingly embed biophysical sensors: textile ECG electrodes for cardiac rhythm, stretchable strain gauges and inertial measurement units (IMUs) for motion and posture, EMG sensors for muscle activation, and pressure-mapping insoles or socks for gait analysis [2]. Environmental sensors for gas exposure and ultraviolet radiation extend the scope of smart clothing beyond the wearer's own physiology into occupational and environmental safety monitoring [1].

C. Power and Data Transmission

Because embedded sensors and radios require continuous power, energy supply is one of the central engineering constraints of smart clothing. Triboelectric and piezoelectric nanogenerators can harvest energy from body motion, and thermoelectric fabrics can exploit the temperature gradient between skin and environment, reducing (though not yet eliminating) dependence on batteries [1]. For data transmission, Bluetooth Low Energy (BLE) and near-field communication (NFC) are the dominant low-power protocols, with woven or printed antennas designed to preserve garment flexibility [1].

IV. ARTIFICIAL INTELLIGENCE FOR GARMENT-GENERATED DATA

As illustrated in Fig. 1, smart clothing operates as a closed loop rather than a one-way sensing pipeline: physiological signals

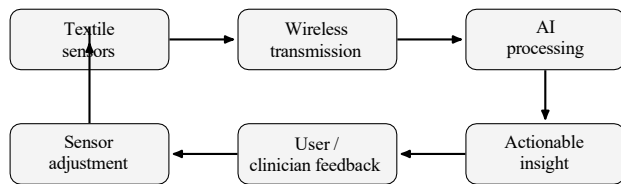


Figure 1: Simplified data flow from textile sensors, through wireless transmission and AI processing, to actionable feedback, closing the loop back to sensing behavior.

captured by embedded sensors are transmitted wirelessly, processed by AI models, translated into insight for the wearer or clinician, and, in adaptive systems, used to adjust subsequent sensor sampling or garment behavior.

A. The Role of AI in Data Processing

A single smart garment can generate a continuous, multi-channel stream of physiological data far too large and noisy to be interpreted manually. AI is therefore central to the value proposition of smart clothing: it filters noise, extracts clinically relevant features, and converts raw signals into actionable alerts or recommendations [1]. Reported applications include AI-driven detection of atrial fibrillation and other arrhythmias from garment-derived ECG traces, prediction of hypoglycemic events from combined glucose, heart-rate-variability, and skin-temperature trends, and rehydration guidance derived from sweat composition analysis [1].

B. Machine Learning and Deep Learning Approaches

Supervised classical models — support vector machines (SVMs), k-nearest neighbors, decision trees, and random forests — remain widely used for activity classification and anomaly detection because of their comparatively modest data and compute requirements, their interpretability, and their robustness on the labeled but noisy datasets typical of wearable sensing [1]. Random forests, for example, have been applied to estimate energy expenditure, detect abnormal gait, and identify falls from accelerometer and pressure-sensor data [1].

Deep learning models are increasingly used where higher accuracy on complex, high-dimensional physiological signals is required. Convolutional neural networks (CNNs) have been applied to ECG-signal interpretation for arrhythmia detection with accuracy comparable to specialist review, and to motion-signal analysis for posture correction [1]. Recurrent architectures, particularly long short-term memory (LSTM) networks, are well suited to the time-series nature of wearable data and have been used to forecast blood-glucose trends and to model heart-rate-variability over time [1]. These models, however, require substantial labeled training data and computational resources that can be difficult to provision on-device, motivating a continued reliance on cloud or edge co-processing.

C. Signal Processing, Anomaly Detection, and Dimensionality Reduction

Adaptive filtering and wavelet transforms are used to remove motion artifacts from photoplethysmography and to decom-

Table 2: AI methods commonly applied to smart-clothing data

Method	Typical application	Main trade-off
SVM / KNN / Decision trees	Activity classification, health-metric classification	Limited scalability, weak on multiclass data
Random forest	Fall detection, dehydration risk	Computationally heavier at scale
CNN	ECG/EEG pattern recognition, posture analysis	Needs large labeled datasets
LSTM	Glucose and heart-rate-variability forecasting	High compute, latency
Autoencoder	Anomaly detection in gait/HRV	Convergence and stability issues

pose EEG and EMG signals into frequency bands relevant to sleep or fatigue monitoring [1]. Unsupervised methods, including K-means and density-based clustering (DBSCAN), support environmental-anomaly detection where labeled examples are unavailable, while autoencoders are used to flag deviations from a wearer's normal gait or heart-rate-variability baseline as an early indicator of injury or cardiovascular anomaly [1]. Feature-extraction techniques such as principal component analysis (PCA) and independent component analysis (ICA) are applied to reduce the dimensionality of multi-sensor sweat and motion data, simplifying downstream classification at some cost to physiological interpretability [1]. Table 2 summarizes representative algorithm families, their smart-clothing applications, and their principal trade-offs.

V. APPLICATIONS

A. Chronic-Disease Management and Fitness

In chronic-disease management, smart garments support continuous, remote tracking of vital signs — heart rate, blood pressure, glucose, and respiratory rate — in conditions such as diabetes, heart failure, and chronic obstructive pulmonary disease, enabling earlier detection of deterioration and, in principle, fewer hospital visits [1]. In sport and fitness, garments with embedded IMUs and EMG sensors support technique optimization, injury-risk monitoring, and team-level load management, as used by systems such as Catapult Sports and Sensoria Fitness [1].

B. Case Study: Stroke Risk Detection and Rehabilitation

Stroke provides an instructive illustration of how smart clothing complements, rather than replaces, medical imaging. Acute stroke diagnosis and treatment planning still depend on rapid, high-resolution imaging: non-contrast CT is the first-line modality for distinguishing ischemic from hemorrhagic stroke, and diffusion-weighted MRI, CT/MR angiography, and perfusion imaging are used to identify salvageable tissue and guide time-critical interventions such as thrombolysis and thrombectomy [2]. These modalities are indispensable in the acute setting

Table 3: Imaging versus smart clothing across the stroke care pathway

Aspect	Imaging (CT/MRI)	Smart clothing
Primary role	Acute diagnosis, treatment eligibility	Risk detection, rehabilitation tracking
Setting	Hospital, specialized equipment	Home, daily activity, rehab clinic
Data type	High-resolution anatomical images	Continuous physiological time series
Time horizon	Single time-point, urgent	Continuous, longitudinal
AI role	Assists image interpretation and triage	Anomaly detection, predictive alerts

but are inherently episodic and hospital-bound.

Smart clothing addresses the complementary, longer-duration phases of stroke care — risk detection, acute-event monitoring, and rehabilitation — that imaging cannot practically cover on a continuous basis [2]. ECG-instrumented smart shirts, such as those used in commercial systems for continuous cardiac tracking, can flag atrial fibrillation, a major modifiable risk factor for recurrent stroke, well before a clinical event occurs. Pressure-sensing smart socks provide continuous gait-asymmetry data that can reveal early mobility decline or post-stroke compensatory movement patterns, while EMG-instrumented garments track muscle activation during neuromuscular re-education, giving therapists objective, continuous feedback rather than relying solely on intermittent clinical assessment [2]. Wearable EEG caps, though less comfortable for extended daily use than shirts or socks, provide insight into neurocognitive recovery during rehabilitation [2].

Table 3 contrasts image-based stroke diagnosis with smart-clothing-based monitoring across several dimensions, underscoring that the two approaches serve different, complementary phases of the care pathway rather than competing directly.

This complementary relationship extends to signal analysis itself: gait heat-maps or postural-deviation plots derived from smart socks or belts are increasingly interpreted using image-processing techniques originally developed for radiological images, illustrating a methodological convergence between imaging analytics and wearable-sensor analytics [2].

Selecting an appropriate garment for a given stage of stroke care involves trade-offs among sensing modality, comfort, and clinical purpose. ECG-based smart shirts and pressure-sensing socks generally offer the best combination of accuracy and unobtrusiveness for everyday risk screening and gait monitoring, since they can be worn like ordinary clothing for extended periods. EEG caps and EMG-instrumented garments provide richer neuromuscular and neurocognitive data but are typically better suited to supervised rehabilitation sessions than to continuous, all-day wear, because of comfort and set-up constraints [2]. Exoskeleton suits and rehabilitation garments such as motorized suits used for gait and arm training occupy a distinct category: they are not primarily sensing platforms but assistive devices, and their embedded sensors are used mainly to calibrate the

level of mechanical assistance to the patient’s residual function [2]. An idealized deployment therefore layers these technologies across the care pathway — lightweight cardiac and motion garments for continuous risk detection and rehabilitation tracking at home, and higher-fidelity EEG or EMG systems reserved for structured clinic-based therapy sessions.

VI. DISCUSSION

Read together, the two strands of evidence reviewed here point to a consistent picture: AI-enabled smart clothing is best understood not as a competitor to established diagnostic tools but as an extension of the care pathway into settings — the home, the gym, the rehabilitation clinic — that conventional imaging and point-of-care instrumentation cannot practically reach on a continuous basis. In stroke care specifically, imaging remains the correct tool for the acute, minutes-matter decisions about thrombolysis or thrombectomy eligibility [2], while smart clothing is best positioned upstream, for modifiable risk-factor detection such as atrial fibrillation, and downstream, for objective, continuous rehabilitation tracking that would otherwise depend on infrequent clinic visits [2]. A similar pattern holds outside stroke care: in chronic-disease management, smart clothing does not replace laboratory diagnostics but narrows the interval between the onset of a physiological deviation and its detection by a clinician.

This reframing has implications for how AI models embedded in smart clothing should be evaluated. Because these garments are intended for longitudinal, largely unsupervised use, model evaluation should emphasize robustness to motion artifact, sensor drift, and inter-subject variability, in addition to the raw classification accuracy typically reported on curated datasets [1]. It also reinforces the importance of the privacy and ethical safeguards discussed below: a device intended to be worn continuously, outside clinical supervision, carries correspondingly greater responsibility for transparent data handling and for minimizing the psychological burden of being monitored [2].

VII. DATA PRIVACY, SECURITY, AND ETHICAL CONSIDERATIONS

Continuous physiological monitoring by smart clothing raises data-protection obligations comparable to those governing other classes of medical devices. Garments can generate large volumes of sensitive personal data — cardiac, motion, and in some cases neurological signals — that require encryption in transit and at rest, informed and revocable consent processes consistent with regulations such as the GDPR, and clear governance over secondary use and third-party sharing [1]. Role-based access control, data minimization, and anonymization or pseudonymization techniques such as k-anonymity are recommended practices for limiting exposure in the event of a breach [1].

Beyond regulatory compliance, ethical deployment requires attention to equitable access, since high device costs can concentrate benefits among populations who can already afford sup-

plementary care, and to the psychological burden of continuous monitoring, which may be experienced by some wearers as a form of surveillance and can affect long-term adherence [2]. Algorithmic bias is a further concern: models trained on non-representative populations risk lower accuracy for underrepresented groups, motivating diverse training data and regular bias auditing as part of clinical validation [2].

VIII. TECHNICAL LIMITATIONS

Despite substantial progress, several technical barriers constrain the transition of smart clothing from prototype to routine clinical tool. Sensor durability under repeated stretching, bending, and laundering remains a leading cause of early performance degradation, and while encapsulation and stretchable substrates have improved resilience, long-term reliability under demanding daily use is still limited [1]. Power supply is a second persistent constraint: batteries add bulk and require recharging, and while energy-harvesting textiles are an active research area, they are not yet a complete substitute for conventional power sources [1]. Signal quality can also be degraded by motion artifacts and electromagnetic interference from nearby electronics, and the absence of industry-wide standards for smart-textile interfaces complicates interoperability across manufacturers [1]. Finally, cost and manufacturing scalability limit affordability, and the evidence base for clinical efficacy — particularly large-scale, prospective validation — remains comparatively thin relative to the pace of device innovation [2].

IX. FUTURE DIRECTIONS

Several converging trends are likely to shape the next generation of smart clothing. In materials, self-healing conductive pathways, biodegradable and bio-based sensor components, and multi-modal energy harvesting (piezoelectric, thermoelectric, and photovoltaic) are expected to improve durability and sustainability while reducing dependence on disposable batteries [1]. In AI, on-device and federated learning approaches can support real-time inference while keeping raw physiological data local to the garment or a paired device, mitigating some of the privacy concerns discussed above [1]. This direction is reinforced by a 2026 perspective arguing that next-generation wearables must move beyond passive, cloud-dependent sensing toward open, modular hardware architectures paired with ultra-low-latency edge intelligence, enabling millisecond-scale, closed-loop responses rather than delayed, retrospective feedback [15]. Clinically, closer integration between wearable data streams and electronic health records, together with AI-driven fusion of imaging and wearable-sensor data, could enable more precisely timed interventions across the prevention-to-rehabilitation continuum illustrated by the stroke case study earlier in this paper [2]. Realizing these directions will require large, prospective clinical trials; standardized evaluation protocols for sensor accuracy and wearability; and continued interdisciplinary collaboration among textile scientists, electrical engineers, data scientists, and clinicians [1, 2].

X. CONCLUSION

Smart clothing, enabled by conductive textiles, embedded electrochemical and biophysical sensors, and AI-driven analytics, is maturing from a novelty into a credible tool for continuous, non-invasive health monitoring. Its value is strongest where continuous, longitudinal data collection is needed — chronic-disease management, athletic performance, and the prevention and rehabilitation phases of conditions such as stroke — rather than as a replacement for time-critical diagnostic modalities like CT and MRI in acute care. Realizing the full clinical potential of smart clothing will depend on resolving persistent challenges in sensor durability, power supply, data privacy, and standardization, and on generating the large-scale clinical evidence needed to move these garments from promising prototypes to validated components of routine care.

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