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# From monitoring to proactive healthcare: Cases exploring embodiment and AI in smart textile design

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**ABSTRACT**
This paper examines the integration of smart textiles and artificial intelligence (AI) in healthcare, focusing on the shift from monitoring to proactive interventions. Through a series of case studies, it identifies generic design challenges and opportunities for proactive healthcare applications and explores design qualities within Smart Textiles, Data & AI, and Embodiment to guide future practices. Findings emphasize the strategic integration of sensors within textile structures, enabling embodied feedback mechanisms, enhancing user engagement and acceptance. Additionally, the study underscores how participatory design approaches can foster long-term health behaviors, reduce burdens on healthcare systems, and enhance patient autonomy by actively involving users and healthcare professionals in the design process. While this work identifies new avenues for proactive and holistic healthcare solutions, it also addresses challenges related to AI-driven data handling, privacy, and ethical concerns, reinforcing the need for transparent, secure, and ethically responsible practices as these technologies advance.

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## Introduction

In many parts of the world the healthcare system today is confronted with significant challenges, including an aging population, an increase in chronic diseases, and limited resources. Consequently, there is a growing need for support and care within patients' homes (Skär and Söderberg 2018). In

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response, healthcare systems globally have adopted a unified approach to the 'cost-effective and secure use of ICT in support of health and health-related fields', commonly referred to as eHealth, as outlined by the WHO (World Health Organization 2024). A key component of this approach is remote health monitoring, utilizing mobile phones, wearable sensors, and artificial intelligence (AI). These eHealth tools enable the development and implementation of integrated, sustainable, patient-centered services, facilitating effective communication between patients and doctors and encouraging active patient participation in the healthcare process (Barello et al. 2015). Furthermore, they contribute to the democratization of healthcare by making certain health services more accessible to all, regardless of the patient's economic resources (Pravettoni and Triberti 2020).

Smart textiles, which possess the ability to measure or respond to stimuli from the user or environment due to their physical properties, have become particularly relevant in healthcare (Tat et al. 2022). These textiles are developed either by integrating conductive fibers, yarns, and fabrics into conventional textile materials through stitching, weaving, and knitting, or by applying a coating of conductive material onto the textile. Smart textiles, offer valuable monitoring and telemetry solutions for individuals with chronic conditions, whether homebound or mobile, including those with congestive heart failure, chronic respiratory diseases, asthma, or diabetes (Meena et al. 2023). Notably, diagnostic smart textiles have recently experienced substantial growth, offering continuous monitoring of biophysical, biochemical, and environmental factors (Libanori et al. 2022). These sensors can provide comprehensive monitoring of biopotential, body temperature, respiratory rate, biochemical parameters, humidity, mobility, and activity levels. Such monitoring capabilities facilitate early detection of issues and enhance the overall health management of individuals (Majumder et al. 2024). Consequently, the medical smart textiles market is projected to surpass US$2 billion by 2027 (Medical Smart Textiles Market 2021). Despite all the international efforts in commercializing smart textile solutions for healthcare, the core focus of main research projects remains on the monitoring, with opportunities left unused, especially in the therapeutic space to support proactive healthcare (Libanori et al. 2022).

In this paper, we reflect on a series of case studies designed by the authors within an academic context, where smart textiles for healthcare combine both monitoring and proactive approaches. Specifically, we discuss how these proactive functionalities are enhanced through the tight integration of data and AI capabilities, driven by the primacy of embodiment in both the research process and the outcomes. Our purpose is to:

1. Identify generic design challenges and opportunities that smart textiles offer for proactive healthcare application.

2. Expose design qualities in the areas of Smart Textiles, Data & AI and Embodiment of the proposed solutions and reflect on their generic value to guide designers.

## *AI-enabled smart textiles in healthcare*

Within the realm of eHealth, P4 Medicine – standing for predictive, preventive, personalized, and participatory – has emerged as a transformative model, shifting healthcare towards a more proactive and individualized approach (Flores et al. 2013). This paradigm moves away from conventional, one-size-fits-all practices towards a data-driven approach to disease management, aiming to enhance patient outcomes and reduce healthcare costs. Precision and personalized medicine offer innovative strategies for disease treatment and prevention by considering individual genetic variations, environmental factors, and lifestyle influences. These approaches increasingly rely on big data and AI technologies (Balthazar et al. 2018). Consequently, research and applications of AI in healthcare have flourished, particularly in specialties that require intensive image interpretation, such as radiology, pathology, gastroenterology, and ophthalmology (Rajpurkar et al. 2022).

Wearables and smart textiles for healthcare play a crucial role in the P4 medicine framework due to their continuous proximity to the body. These devices generally fall into two main categories: primary devices, which operate independently with integrated processing and connectivity, and secondary devices, which perform specialized tasks while relying on primary devices for data processing (Godfrey et al. 2018). Some wearable devices function autonomously, utilizing closed-loop systems that self-regulate through analyte-induced physicochemical reactions (Libanori et al. 2022). In addition, advances in fabric-based edge intelligence involve the development of smart e-textiles featuring conductive fibers inspired by spiking neural networks (SNN), mimicking artificial neurons and synapses to enable on-garment AI (Cleary et al. 2023). AI technologies, including ML and Deep Learning (DL), have significantly enhanced smart textiles through capabilities in data analysis, pattern recognition, and predictive modeling. For instance, a bionic heat-adaptive textile employs biomimetic microstructure design for dynamic thermal regulation, enabling sweat absorption and multi-parameter colorimetric sensing, thus offering adaptive, energy-efficient personal heat stress management (Chow et al. 2025). Another project developed a sensor-integrated knit to enable spatiotemporal mapping of pressure distribution for adolescent idiopathic scoliosis (Lee, Wang, et al. 2025). The same team also implemented a DL model based on multilayer perceptron (MLP) to intelligently recommend insole materials through footprint image analysis developed for diabetic foot protection (Zhang, Ma, et al. 2024), combined with gait dynamics analysis to understand the biomechanical effects of velocity on foot parameters, guiding functional insole design (Zhang, Liu, et al. 2023). In terms of comfort, intelligent thermochemically heated e-textiles combined with AI-driven temperature control systems have been developed to meet diverse thermal needs in healthcare products (Lee, Tan, et al. 2025).

Most wearables adhere to a model involving data collection, analysis, and clinical intervention, managed either by the device itself or via connectivity to cloud-based systems. Cloud platforms or external devices often utilize ML algorithms to help smart textiles adapt to individual user requirements, particularly addressing the evolving healthcare needs associated with aging (Loke et al. 2020). Privacy is a significant consideration when integrating these technologies, necessitating robust electronic health record (EHR) management platforms that protect personal information and enhance system usability (Assenza et al. 2020).

Additionally, the integration of AI introduces further risks that require careful management. A recent EU report on AI in healthcare (European Parliamentary Research Service 2022) outlined seven major AI-related risks: patient harm due to AI errors, misuse of medical AI tools, AI-driven biases perpetuating inequities, lack of transparency, privacy and security concerns, accountability gaps, and implementation obstacles. Another key contribution to AI ethics is the global landscape of AI ethics guidelines, which identified eleven critical ethical issues based on a comprehensive review of AI ethics guidelines applied broadly (Jobin, Ienca, and Vayena 2019). These identified themes have subsequently been examined and updated through a literature review, offering specific mitigation strategies for designers to manage and reduce these ethical risks effectively (Li, Ruijs, and Lu 2022).

## *Embodied smart textiles for healthcare*

Previous efforts have explored smart textiles and wearables through the concept of embodiment, particularly examining how digital information integrates with our perceptual-motor skills and how data can, in turn, be fed back into the sensorimotor system to trigger actions – essentially, using information for action (ten Bhömer, Tomico, and Wensveen 2016). Moreover, the concept of ultra-personalization illustrates how an embodied approach to personalization can evolve by using the data trail of a product as a narrative to guide the design of future generations (Nachtigall et al. 2019). Smart textiles, due to their embodied nature, hold the potential to provide therapeutic functions by interacting with the human body, offering both continuous and one-time therapeutic solutions. These textiles can adjust treatments based on an individual's changing health profile, allowing for a dynamic, personalized approach to healthcare (Libanori et al. 2022).

Given their close proximity to the body, wearables and fashion technologies have the potential to drive a 'next wave' in the social and aesthetic dimensions of technology, as these interactions become more deeply integrated into daily life (Tomico et al. 2017). However, research shows that wearables in healthcare still face considerable challenges regarding user acceptance and long-term adoption. These difficulties largely stem from the fact that the design and implementation of such technologies often fail to consider users' needs and the specific contexts in which they will be used (Gorini et al. 2018). One potential approach to reducing the rejection of health monitoring devices, as suggested by other authors, is to begin with the individual who is 'allowed to dream'. This perspective seeks to create a new paradigm that prioritizes a humanistic approach to designing wearable health technologies beyond the medicalization of wearables (Møller and Kettley 2017). For instance, smart garments have been employed to bridge VR technology and user experiences, enhancing immersive self-healing practices (Hu et al. 2018). Furthermore, ensuring user comfort and addressing potential technological anxiety and resistance are essential for the successful integration of novel healthcare technologies (Tsai et al. 2020). Sustainability considerations also play a crucial role in the effective application of smart garments in healthcare settings (Chen and Chiu 2022).

Theories of embodied interaction have shown that the context in which activities around the interface occur is not only relevant but also gives meaning to these interactions (Dourish 2001). In the case of chronic conditions, self-monitoring and other eHealth solutions are seen as critical technological enablers, although they are often deployed in sensitive settings. Healthcare professionals must move beyond focusing solely on tasks and disabilities to also consider individuals' emotions and attitudes toward these assistive devices. Additionally, they must be aware of the social and cultural meanings associated with both disability and technology, as these factors influence how individuals accept and integrate these devices into their lives (Hocking 1999). From the perspective of Computer-Supported Cooperative Work (CSCW), attention should also be given to auxiliary stakeholders around the patient – administrative staff, allied health professionals such as therapists and pharmacists, ancillary staff like domestic carers, and family or informal caregivers (Fitzpatrick and Ellingsen 2013). Similarly, eHealth services in healthcare should adhere to a person-centered approach, with healthcare professionals' knowledge and commitment ensuring that patient care remains safe, secure, and accessible for both patients and their families (Skär and Söderberg 2018).

Effective embodied interactions are particularly vital for telemedicine applications, with research exploring emotional regulation through smart garments for healthcare providers themselves (Jiang et al. 2024). Smart garments have also shown promise in supporting speech therapy for adults with dysphagia and speech disorders (Nissinen et al. 2021), enhancing spatial perception and navigation for the visually impaired (Bhatlawande et al. 2024), and assisting at-home dementia care through integrated clothing-related smart aids (Zgonec and Bogataj 2023). These applications illustrate smart textiles' potential to enhance independence, privacy, and quality of life for special populations.

In the following sections of this paper we will introduce the smart textiles design cases, after which we will discuss specific design challenges and opportunities.

## Cases

This section introduces a series of smart textile systems developed by the authors to address specific healthcare challenges through therapeutic and proactive interventions. Each case is presented as a short textual and visual introduction, and is briefly described across three dimensions. *Smart Textile Design* examines the selection of materials and integration techniques, with attention to flexibility, conductivity, and wearability. *AI & Data* explores how ML and, in some cases, traditional algorithms are employed to process data collected via wearable sensors, supporting health monitoring, condition prediction, and personalized feedback. *Embodiment* addresses the strategic placement of sensors in relation to the body to maximize comfort and efficacy, as well as the contextual and ergonomic integration of the design into everyday use.

### *Scoliosis correction system*

This system predicts postures that may worsen scoliosis by monitoring the Angle of Trunk Rotation (ATR), enabling early risk identification and promoting corrective habits. Through continuous monitoring and visual feedback, it helps prevent scoliosis progression by encouraging posture adjustments. Users receive personalized correction plans based on their spinal data, ensuring tailored interventions. The system includes a mobile app featuring a giraffe-themed virtual pet to engage adolescents and motivate participation in exercises (Figure 1). Experiments with 12 adolescent patients validated the system's effectiveness in ATR prediction accuracy, posture correction, and

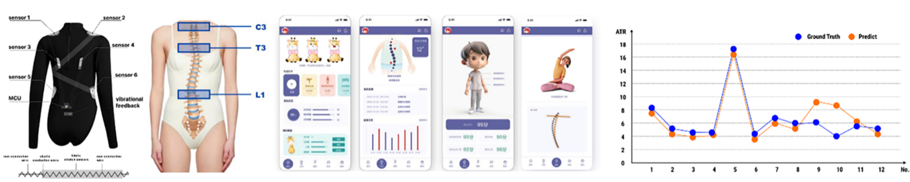


**Figure 1.** (a) Scoliosis monitoring system prototype and sensor placement; (b) APP-based visual feedback interface; and (c) ATR prediction results for 12 subjects.

usability. Further research will focus on enhancing ATR monitoring accuracy and long-term comfort.

### *Smart textile design*

The system incorporates textile strain sensors and elastic conductive wires composed of silver fibers, sewn into the garment with zigzag stitching to secure components while maintaining fabric flexibility. A data collection module enables real-time tracking of spinal posture, assessing spinal deformities, and calculating ATR. A feedback module delivers actionable insights through vibration alerts and a mobile app, guiding users in posture correction.

### *AI & data*

The system collects real-time data on spinal curvature and movement through embedded sensors. Data is preprocessed to remove noise, then analyzed by an Long Short-Term Memory (LSTM) algorithm, which classifies posture patterns and detects scoliosis-related deviations. This approach supports immediate posture correction and anticipates potential changes in spinal alignment.

### *Embodiment*

Sensor placement is based on scoliosis biomechanics and typical spinal deformation areas. Using optical capture to measure spinal deformation, body posture was analyzed to design an optimal layout for six textile strain sensors in critical areas for monitoring spine curvature and postural deviations (Zhang, Chen, et al. 2024). The system provides dual feedback: haptic (vibrotactile) feedback for immediate, intuitive posture correction and visual feedback via a mobile app, which enhances user engagement through progress tracking and personalized insights.

## ***Smart legging for posture monitoring***

The smart leggings use resistive textile sensors and ML algorithms to detect improper running postures, enabling early intervention to prevent musculoskeletal issues (Wang et al. 2024). By identifying incorrect postures and providing real-time vibrotactile and auditory feedback, the leggings help users adjust their form, reducing injury risk and promoting long-term health. Personalized sensor placement enhances precise posture monitoring. With a deep-learning model achieving 99.1% accuracy, the system has been tested for robustness and received high user satisfaction, although adapting to different body types and running styles without recalibration remains challenging (Figure 2).

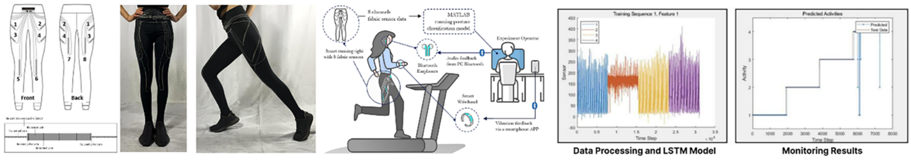


**Figure 2.** (a) Structure and prototype of smart pants for running posture monitoring (left); (b) monitoring and feedback system architecture (middle); and (c) processing of data and posture classification results using the LSTM model (right).

### *Smart textile design*

The leggings feature conductive elastic webbing made from silver fibers, polyester, and elastomeric yarn, providing both stretchability and conductivity. Copper-based yarns connect the sensors to the processing unit, with sensors sewn into the fabric using zigzag stitching. Snap buttons and soft electronic interfaces secure the textile sensors to the processing unit. Positioned on the knees, thighs, and hips, these sensors capture motion data, which a microcontroller processes for analysis by an LSTM algorithm on a PC. Real-time feedback is delivered through vibrotactile and auditory cues, assisting users in adjusting their posture.

### *AI & data*

Sensors embedded in the leggings capture strain and deformation data, which is processed by an onboard microcontroller before being analyzed by an LSTM neural network. The system classifies posture into three categories: correct posture, internal knee rotation, and hip displacement. Real-time feedback, delivered through auditory cues or vibrotactile feedback, helps users correct posture immediately, aiding in injury prevention and enhancing running efficiency.

### *Embodiment*

Sensors are strategically placed on the knees, thighs, and hips to capture key movement data relevant to common running injuries. Placement minimizes interference from friction-prone areas, maintaining sensor integrity and user comfort. Vibrotactile feedback provides intuitive sensations that align with sensory receptors, allowing natural posture adjustments, while auditory cues offer non-visual guidance, keeping users focused on their activity.

## *E-MotionWear for emotion regulation*

*E-MotionWear* is a smart T-shirt designed to regulate emotions through upper-body movement-based interactions for healthcare workers (Jiang et al. 2024) and high-stress environments (Jiang et al. 2021). It leverages the *Somatic Marker Hypothesis* (Damasio 1999), which posits that deliberate body movements can influence emotional states by encouraging posture adjustments linked to positive affect. The system combines real-time movement detection with multi-modal feedback to foster emotional self-regulation. Unlike passive monitoring tools, E-MotionWear adopts a proactive approach, bridging therapeutic wearables with embodied interaction. Its design targets specialized groups like healthcare workers, future research aims to explore broader applications for daily emotion management.

## *Smart textile design*

The *E-MotionWear* prototype integrates four textile-based motion sensors into a stretchable jersey T-shirt to detect upper-body movements: elbow flexion/extension, shoulder flexion/extension, open/closed arms, and neck flexion/extension. Sensors for elbow, shoulder, and arm movements utilize knitted elastic textile sensors, while neck movements are tracked via a layered textile sensor for bending detection (see Figure 3a). Stainless steel conductive threads connect textile sensors to a microcontroller, secured with zigzag stitching to maintain flexibility and durability during motion. Besides, users can select between audio feedback mode (via an MP3 module) or vibrotactile feedback mode (via coin motors) depending on their usage scenarios. The prototype prioritized seamless integration with everyday clothing, using soft electronic interfaces and avoiding rigid components. The textile sensing system makes the prototype comfortable to wear, so healthcare workers can wear it under their uniforms in their workplaces (Jiang et al. 2024), see Figure 3c.

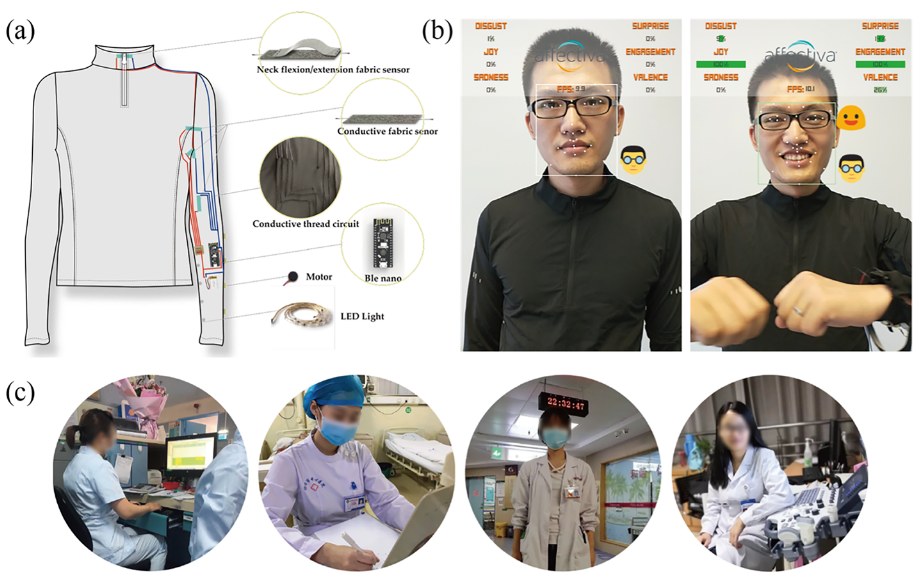


**Figure 3.** (a) The *E-MotionWear* system; (b) facial expression recognition of participants during lab experiments; and (c) healthcare workers using the system in a work setting.

### AI & data

While the current prototype does not employ AI, data from textile sensors is preprocessed to filter noise and map movements to feedback mechanisms. Sensor signals (e.g. resistance changes during elbow flexion) are transmitted via Bluetooth to a mobile app, which triggers audio or vibrotactile responses in the lab experiment. Quantitative analysis using the Self-Assessment Manikin (SAM) revealed significant increases in emotional valence and arousal during shoulder flexion and open-arm movements. Facial emotion analysis via the AffdexMe App showed higher engagement with vibrotactile and audio feedback modes compared to visual feedback mode. The study emphasizes future AI integration for dynamic calibration, such as motion recognition and adjusting sensor sensitivity for diverse body types using ML (Jiang et al. 2021).

### Embodiment

The system's embodied interaction framework centres on real-time, non-intrusive feedback aligned with sensory-motor loops. The study validated the *Somatic Marker Hypothesis*, showing that expansive movements and upward movements correlated with positive emotional effects. Vibrotactile feedback and audio feedback modes were preferred for their intuitive guidance, enabling users to adjust movements without visual distraction.

Sensor placement prioritized ergonomic integration: elbow and shoulder sensors were embedded along joint flexion points, while neck sensors were positioned at the cervicothoracic junction. This design minimized interference with natural movement. However, challenges like sensor-skin displacement during neck flexion highlighted the need for biomechanically optimized layouts. In general, participants reported positive experiences with the shirt's comfort and psychological aesthetics. Field studies demonstrated the T-shirt's positive impact on healthcare workers' immediate emotion regulation, contributing to a more positive attitude toward their work.

## SoftCentral smart cushion for health monitoring

The SoftCentral cushion promotes preventive healthcare for elderly users by non-intrusively monitoring seating behavior, reducing sedentary habits, detecting poor posture, and tracking geriatric health parameters (Xie et al. 2020). Eight embedded pressure sensors capture pressure distribution, identifying postures like slouching and standing, and provide real-time feedback and personalized exercise recommendations (Figure 4). Remote monitoring allows family members or healthcare professionals to receive alerts when health thresholds are exceeded, supporting both emergency response and daily care. The prototype has been validated through lab testing and user interviews, demonstrating its usability and potential for long-term


**Figure 4.** (a) Pressure sensors positioned for posture monitoring; (b) ergonomic cushion design with replaceable cover; (c) person using the cushion; and (d) application interface displaying real-time data and exercise guidance.

monitoring. Further research is needed to enhance sensing accuracy and address concerns regarding reliability.

### *Smart textile design*

The cushion features eight piezoresistive pressure sensors (Velostat) embedded beneath the upper textile layer, connected with silver-based conductive yarns. Early prototypes used conductive ripstop fabric for flexible traces, while later versions incorporated traces directly into the fabric through circular knitting. A detachable, magnetized box connects to the conductive threads and houses an ESP32 microcontroller and RF wireless module.

### *AI & data*

The microcontroller processes sensor data, analyzing sedentary behavior, posture, and movement through algorithms that extract parameters like sitting duration, pressure balance, and movement speed. A timer tracks prolonged sitting, and posture analysis includes pressure balance metrics, while movement parameters focus on shifts and rise-up speed. Data is transmitted via the MQTT protocol to an application that provides visual feedback for posture correction and suggested exercises. Although the algorithms were optimized through lab studies, future iterations may explore ML for further refinement.

### *Embodiment*

Although the cushion is not a wearable device, its interaction paradigm is embodied. The contoured surface guides the user's hips toward the sensor zone through affordances inherent in the geometry, eliminating the need for explicit instruction. Posture monitoring and low-intensity activities, such as repeated sit-to-stand transitions, align with the user's habitual movements, converting everyday actions into data-rich feedback. By employing familiar upholstery materials and domestic proportions, the cushion integrates seamlessly into the living environment and promotes sustained engagement. Sensors are embedded within the textile layers so that their texture and placement maintain comfort and do not disrupt routine use, a feature that is particularly advantageous for older adults who often find tangible interfaces more accessible than smartphone-based applications.

### *Vigour cardigan keeping people active*

The *Vigour* cardigan is specifically designed for elderly patients with Alzheimer's disease, incorporating wearable technology to support motor skill rehabilitation and track progress (ten Bhömer, Tomico, and Hummels 2013; ten Bhömer and van Dongen 2014). It aids therapists by optimizing rehabilitation sessions, ensuring exercises are appropriately challenging, and reducing the need for manual monitoring. Integrated stretch sensors track arm and lower back movements, sending real-time data to an application that provides auditory feedback, enabling immediate responses to user movements. Sensor sensitivity can be adjusted via the application interface for personalized calibration (Figure 5). The cardigan was developed through a participatory design approach, allowing physical therapists to actively test and refine both the cardigan and its associated application throughout the development process. Rather than providing medical treatment directly, the cardigan functions as a physical activity tool to make fundamental exercises, such as arm lifting and chair-based movements, more engaging for patients.

### *Smart textile design*

The stretch sensors, made from Bekinox yarns (stainless steel and wool), are connected with Ohmatex elastic cables. The cardigan is knitted on a knit-and-wear machine, with sensor areas and tubular structures seamlessly integrated. Adhesive

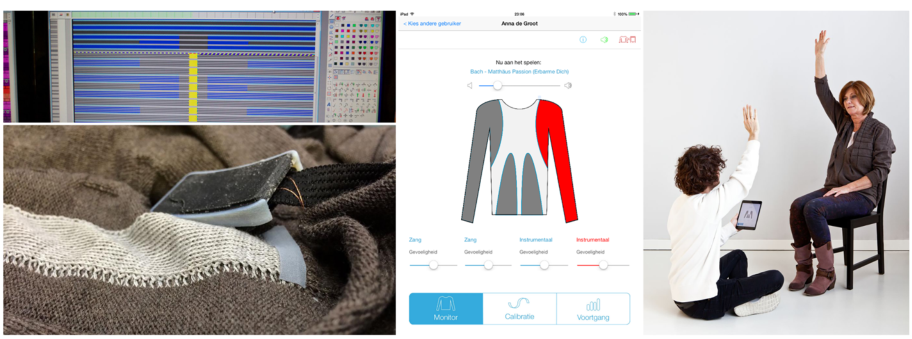


**Figure 5.** (a) Sensor knitting and tunnel construction; (b) therapist application interface connecting auditory feedback to movements; (c) scenario with therapist and patient using the cardigan.

bonds the sensors to conductive yarns for electronic connections. A 3D-printed neck casing houses the battery and Bluetooth transmitter, with each sensor linked to a custom PCB inside detachable casings, allowing for easy washing.

#### *AI & data*

The garment includes four sensors: two on the lower back and two under the arms, capturing movement presence and speed. Actions such as arm lifting or back bending are translated into auditory signals tailored to each patient (e.g. a patient who prefers piano music may hear scales of piano chords) via an iPad application. Both sensor sensitivity and feedback can be customized according to individual patient capabilities, offering a tailored rehabilitation experience. A crucial design decision was to empower physical therapists with full control over how data translates into musical feedback, avoiding predefined judgments of 'correct' or 'incorrect' movements.

#### *Embodiment*

Designed to resemble a conventional cardigan, *Vigour* aims to minimize stigma and promote acceptance among elderly users. From this perspective, merino wool was selected to reinforce the garment's identity as everyday clothing rather than a medical wearable device. During initial consultations, healthcare professionals assess the patient's physical condition and measurements, allowing for the creation of personalized garments with optimally placed sensors tailored to specific rehabilitation needs. Movement sonification offers supplementary sensory feedback, enhancing patient engagement and providing guidance throughout rehabilitation exercises.

### *Wearable FES-sEMG system*

The system utilizes textile-based electrodes to recognize lower limb motion and muscle fatigue while providing functional electrical stimulation (FES) (Zhang, Bai, et al. 2024). Traditional FES devices used in rehabilitation face challenges in wearability, motion intention recognition, and fatigue detection. This developed system addresses these limitations by incorporating customized textile electrodes for enhanced comfort and integrating surface electromyography (sEMG) to monitor movement and fatigue (Figure 6). A deep-learning model provides real-time feedback, independent of electrical stimulation, enabling continuous daily use without professional supervision. Future clinical trials will evaluate its efficacy in rehabilitation settings.

#### *Smart textile design*

The textile electrodes, made from conductive fabric with Ag/AgCl yarn and a sponge lining, provide enhanced fit, flexibility, and reduced skin irritation,

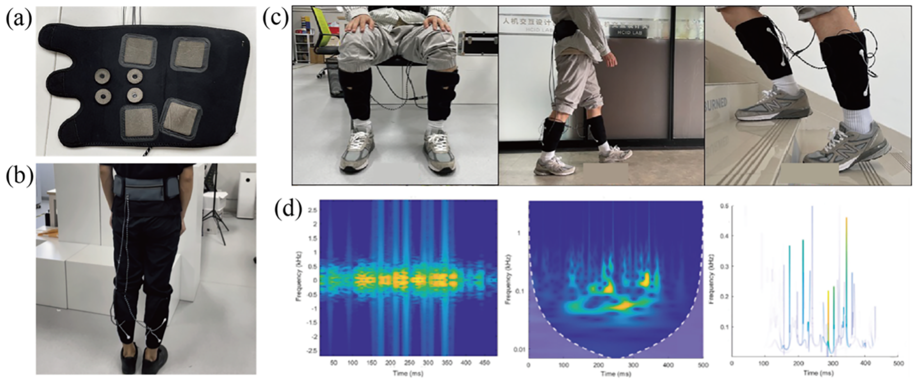

Figure 6. (a) FES-sEMG prototype; (b) participants wearing the prototype; (c) sitting, walking, climbing experiment; and (d) 500-ms-long sEMG time-frequency images with various imaging methods.

making them ideal for long-term monitoring. The wearable device combines these electrodes with an sEMG-FES module, featuring a microcontroller, sensors, and Bluetooth communication. A GUI supports real-time configuration and monitoring of lower limb motion and muscle fatigue.

### *AI & data*

Due to the relative displacement between fabric electrodes and skin, a parallel-structured DL model is used to identify movement and muscle fatigue without interference from electrical stimulation. The system analyzes sEMG signals collected through customized textile electrodes, enabling it to recognize different motions and fatigue states in real-time. This closed-loop, user-driven system adjusts the electrical stimulation based on the user's physical state, offering a personalized rehabilitation experience. The continuous monitoring and adaptability enhance long-term usability and comfort, differentiating it from traditional FES devices.

### *Embodiment*

The system features leggings with integrated fabric electrodes ergonomically placed according to the calf's 3D morphology, enabling precise positioning without specialist help. Fabric electrodes are seamlessly attached to the substrate via a heat-adhesive process, with fabric materials and Velcro enhancing comfort. Detachable electronic components allow the leggings to be machine washable.

## Discussion

In this section, we further reflect on the previously described case studies, conducted by the authors within an academic context, which explore smart textiles for healthcare by integrating both monitoring and therapeutic functions. The discussion is framed around the P4 medicine model: predictive, preventive, personalized, and participatory (Flores et al. 2013). We address several critical aspects, including the design challenges and opportunities in proactive healthcare applications, the design qualities of smart textiles, data, AI, and embodiment, and their potential to inform future design practices. These themes provide the basis for analysing the practical and theoretical contributions of the case studies, particularly regarding proactive health, whole-body sensor placement, and data processing capabilities.

## Predictive health

The predictive aspect of P4 medicine emphasizes identifying health issues before they manifest, allowing for early intervention. AI and advanced data algorithms in smart textiles play a crucial role in this predictive capacity.

### AI and machine learning applications

The *Wearable FES-sEMG System* exemplifies the use of DL models to analyze sEMG signals. By distinguishing different types of lower limb motions and identifying muscle fatigue, the system can predict when a user might need to adjust their activity levels or seek medical attention. This closed-loop system automatically modifies electrical stimulation in response to the user's physical state, optimizing the rehabilitation process. Similarly, the *scoliosis correction shirt* preprocesses sensor data to remove noise before feeding it into a LSTM model. The LSTM algorithm classifies posture deviations and monitors scoliosis progression over time. By capturing time-dependent movement features, the system can predict worsening conditions and prompt timely corrective actions. In the *knee injury prevention leggings*, LSTM models classify improper running postures based on data from integrated resistive textile sensors. Real-time analysis allows immediate feedback to users, predicting potential injury risks and enabling preventive measures.

### Challenges and future directions

While these AI applications enhance predictive capabilities, they also present challenges. Accommodating different body types and movement patterns can be complex. The *E-motionWear shirt*, which uses sensors to detect specific body movements, could benefit from AI that dynamically adjusts sensor positions to individual users, improving predictive accuracy. The *SoftCentral cushion* faced difficulties in setting appropriate pressure thresholds for different users. ML could optimize these thresholds by learning from user-specific data, enhancing the cushion's ability to predict and prevent poor posture. Furthermore, the predictive power of AI in smart textiles raises important ethical and privacy concerns. Collecting sensitive physiological data necessitates strict data security, informed consent, and transparent handling processes. For example, the *SoftCentral system* uploads health information to cloud-based services, requiring robust security to prevent unauthorized access. Ethical approvals and transparent data handling are essential to maintain user trust across all case studies.

## Preventive health

Preventive health focuses on interventions that avert the onset of diseases or injuries. The case studies showcase how smart textiles facilitate preventive measures through continuous monitoring and immediate feedback.

### Embodied interaction

Following the principles of embodied interaction (Dourish 2001; ten Bhömer, Tomico, and Wensveen 2016), the *scoliosis correction shirt* and the *E-motionWear shirt* utilize vibrotactile feedback to guide users toward desired behaviors. The *scoliosis shirt* prompts users to adjust their posture through haptic signals, preventing further spinal curvature. The *E-motionWear shirt* encourages movements that mitigate negative emotional states, such as stress or anxiety, by providing real-time feedback through vibrotactile, auditory, and visual cues. Movement-based interactions are central to preventive strategies. The *E-motionWear shirt* targets specific gross body movements, like shoulder flexion and arm openness, known to promote positive emotions. By reinforcing these movements, the shirt helps users prevent stress-related health issues, especially in high-stress environments like healthcare settings. The *smart leggings for knee injury prevention* offer auditory feedback during running sessions. By providing direct guidance on adjusting running posture, the leggings help prevent injuries through continuous and tailored intervention. The *SoftCentral cushion* encourages users to maintain proper sitting posture, preventing back pain and associated health problems by guiding users through exercises that strengthen core muscles.

### Therapeutic care

The *Wearable FES-sEMG System* combines therapy with proactive monitoring. By recognizing lower limb motion and muscle fatigue, it provides real-time feedback independent of the stimulation itself. This allows users to strengthen weakened muscle groups as needed, preventing deterioration without constant supervision from healthcare professionals. Preventive and therapeutic health also encompasses psychological well-being. The *scoliosis correction shirt's* integration of a giraffe-themed virtual pet gamifies the rehabilitation process, encouraging consistent use and reducing the psychological burden for adolescents. The *Vigour cardigan* supports social interaction during rehabilitation exercises, promoting both physical and social well-being among elderly patients by encouraging group activities.

### *Personalized health*

Personalized health tailors medical interventions to individual characteristics, needs, and preferences. Smart textiles enhance personalization through customizable feedback and adaptive sensor integration.

#### *Customized feedback*

The *smart leggings for knee injury prevention* provide personalized auditory feedback, offering specific instructions on adjusting running posture. This tailored guidance helps users prevent injuries based on their unique movement patterns. The *Vigour cardigan* generates auditory feedback based on sensor activity, allowing users to adjust rehabilitation exercises in real-time. Sensor sensitivity and activation can be customized via the interface, providing personalized calibration for each patient. Personalization extends to user experience, impacting long-term adherence to health interventions. The *SoftCentral cushion's* design resembles an ordinary home item, reducing stigma and encouraging integration into daily life. Although the impact on long-term adherence was not evaluated in the case studies, it represents a potential area for future research.

#### *Sensor integration*

Smart textiles enable whole-body monitoring, which is crucial for the integration of eHealth solutions, where the continuous proximity of textiles to the body facilitates a seamless interface for both monitoring and therapeutic purposes (Godfrey et al. 2018). The *scoliosis correction shirt* uses an optical capture system to map spinal and skin deformation, informing the precise placement of textile sensors. Sensors are strategically positioned over the thoracic and lumbar vertebrae and the trapezius muscle to maximize therapeutic efficacy. In the *Vigour cardigan*, knit-and-wear technology seamlessly integrates sensors into the textile, creating a personalized and ready-to-wear rehabilitation solution for older adults. The *SoftCentral cushion* employs bespoke circular knitted fabric for accurate pressure sensor distribution, enhancing functionality for posture correction. Methods like zigzag stitching ensure sensors remain securely in place while accommodating individual body movements. This technique is applied in the scoliosis correction shirt, running leggings, and *E-motionWear shirt*, allowing the garments to move naturally with the body while maintaining sensor accuracy.

### *Participatory health*

Participatory health emphasizes collaboration among patients, healthcare professionals, and designers to create effective health solutions. The case studies highlight the importance of involving stakeholders throughout the development process.

### *Collaborative design processes*

The *Vigour cardigan* was developed through collaboration with therapists, eldercare managers, and designers. This participatory approach ensured the final product met the needs of both users and healthcare providers. Similarly, the *E-motionWear shirt* was evaluated by healthcare personnel in real-world settings, providing insights into usability and comfort. In the *scoliosis correction shirt* project, interviews with six scoliosis specialists informed the design of textile sensors and personalized correction plans. Engaging both experts and patients enhanced comfort and psychological acceptance, making the shirt more appealing to adolescents.

The *SoftCentral cushion* incorporated feedback from healthcare professionals, family members, and users across age groups. Semi-structured interviews allowed for adaptations that increased user acceptance and potential adoption of mobile health technologies.

### *Alleviating healthcare burden*

Participatory design in smart textiles contributes to alleviating the burden on healthcare systems, aligning with the eHealth framework's goal of fostering patient-centered care and enhancing healthcare accessibility (Barello et al. 2015; Skär and Söderberg 2018). Devices like the *E-motionWear shirt* can reduce workplace absenteeism by managing stress, maintaining an effective workforce. The *knee injury prevention leggings* may decrease the need for physiotherapy interventions, reducing healthcare workload. The *scoliosis correction shirt* minimizes frequent specialist visits by promoting ongoing, proactive care. The *Wearable FES-sEMG System* enables patients to perform therapeutic rehabilitation independently at home, easing the strain on inpatient services. The *Vigour cardigan* supports physical rehabilitation therapists in improving patient outcomes and helps older adults remain active, potentially reducing demand for long-term care. These smart textile systems align with the WHO's eHealth strategy by making healthcare more accessible, cost-effective, and patient-centered, ultimately enhancing care delivery efficiency (Bashshur et al. 2011; World Health Organization 2024).

### *Ethical and privacy concerns*

Trustworthiness and accountability are essential in AI applications, particularly in health-related contexts. This is especially important for the smart textile-based health devices discussed in our overview, as they continuously collect sensitive physiological data such as user posture, muscle activity, and movement. These data are gathered through integrated garment sensors or supplemented by methods such as questionnaires and interviews, providing insights for design refinement.

Given that the discussed cases predominantly occurred within academic contexts, the Global Landscape of AI Ethics guidelines concerning privacy, transparency, and informed consent played significant roles (Jobin, Ienca, and Vayena 2019). To safeguard participant welfare, ethical approvals were explicitly obtained in these cases. For instance, the *SoftCentral* study received approval from the university's Ethics Committee to protect older adults during interviews and prototype assessments. Similarly, the *Wearable FES* System study secured approval from the University Medical Ethics Committee, ensuring participants provided informed consent and understood their rights clearly. The *E-motionWear* study followed a comprehensive ethical protocol, including informed consent forms and careful handling of privacy concerns by minimizing unnecessary video recordings. Projects involving vulnerable groups, such as *SoftCentral*, often initially conduct lab-based design evaluations before direct engagement with these populations.

To mitigate ethical issues, multi-stakeholder engagement and co-creation throughout development are recommended strategies, aligned with EU parliamentary recommendations for AI and Health (European Parliamentary Research Service 2022). This participatory approach was utilized in several case studies. For example, the *Vigour* cardigan project actively involved healthcare professionals and patients, ensuring the final product met standards of comfort, safety, and dignity, particularly for older adults with Alzheimer's disease. The *E-MotionWear* project similarly engaged healthcare workers during early prototype evaluations, while the *SoftCentral* project incorporated ongoing input from elderly individuals, their family members, and healthcare staff throughout the project, guiding design decisions comprehensively.

## Conclusion

This study aimed to answer two core questions: What are the generic design challenges and opportunities that smart textiles offer for proactive healthcare applications? And what design qualities in the areas of Smart Textiles, Data & AI, and Embodiment can guide future designers?

To address these questions, we explored the design challenges and opportunities presented by smart textiles for proactive healthcare applications, drawing on case studies that illustrate the combination of monitoring and proactive therapeutic functionalities. Smart textiles represent a promising shift from reactive healthcare models towards proactive, preventive approaches aligned with the P4 medicine model, which emphasizes predictive, preventive, personalized, and participatory care. Through the tight integration of data and AI, combined with an embodied approach, these technologies extend the role of wearables beyond monitoring, positioning them as holistic tools for health management.

The generic design challenges identified include sensor integration, ensuring user comfort, and long-term adoption. Smart textiles, by nature, are complex systems that must consider the ergonomic and contextual interactions of the human body to ensure a seamless user experience. The discussed case studies highlighted that successful solutions address these challenges through innovative sensor mapping methods, flexible fabrication techniques, and user-centric approaches to system embodiment. The integration of data and AI plays a critical role in adapting smart textiles to the specific needs of individuals, offering personalized and context-aware interventions. Techniques like LSTM algorithms and DL models effectively support real-time analysis and provide adaptive responses that improve user engagement. Moreover, the focus on embodiment and whole-body interaction underlines the unique qualities of smart textiles that distinguish them from traditional wearable technologies. Embodied feedback – such as vibrotactile, auditory, and visual cues – emphasizes the tight coupling between perception and action, helping users intuitively adjust behaviors to improve health. This embodied design approach further supports the acceptance and integration of these devices into everyday life.

However, several critical issues must be addressed to realize the capabilities of smart textiles in healthcare. One significant challenge is the long-term user adoption of these technologies. While initial engagement may be high, the novelty effect can wear off, leading to decreased usage over time. Ensuring that smart textiles remain comfortable, user-friendly, and non-intrusive is essential for sustained adoption. Additionally, the cost of production and maintenance of these advanced textiles may limit their accessibility, especially for lower-income populations, thereby posing a barrier to achieving equitable healthcare solutions. Another critical concern is data privacy and ethical considerations. The integration of AI and continuous health monitoring raises questions about the security and ethical use of personal health data. Users must be assured that their data is protected and used responsibly, and clear consent processes need to be in place. Without addressing these privacy concerns, user trust in smart textile solutions could be compromised, hindering broader adoption.

In conclusion, the case studies and our reflections suggest that smart textiles hold substantial promise to transform healthcare into a more proactive, personalized, and embodied experience. By addressing the challenges of sensor integration, leveraging data and AI for personalization, and ensuring a user-centric design approach, smart textiles can significantly contribute to more effective, sustainable, and accessible healthcare solutions. Future work should continue to explore the long-term user adoption of these devices, evaluate their sustained health impact, and refine the integration of ethical considerations related to data privacy and user empowerment.

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