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POTENTIAL OF SMART FABRICS IN PASSIVE STIMULATION OF MUSCLE MEMORY

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Abstract. *The article focuses on analyzing the potential of intelligent textile materials in the context of their ability to passively stimulate muscle memory, with applications in medical, rehabilitation, and everyday settings. The aim of the study is to systematize the scientific and technical foundations for the development and functioning of smart fabrics designed to perform biofunctional tasks in healthcare, rehabilitation, and domestic environments. The study employed general scientific methods of cognition, including analysis, synthesis, classification, systematization, comparison, and generalization. The results show that smart textiles represent a high-tech integrative system that combines sensors, actuators, energy units, communication modules, and computing devices integrated into the textile structure. These systems are based on functionalized fibers, which are classified according to their architecture (monocomponent, coaxial, composite, coated) and are produced using advanced technologies such as melt spinning, wet spinning, electrospinning, coaxial spinning, dip coating, in situ polymerization, self-assembly, and 3D printing. These technologies ensure scalability, flexibility, stability, and the ability to apply microstructured functional layers, enabling the creation of fibers with electrical, optical, chemical, or mechanical properties. It is concluded that smart textiles serve five key functions: sensing (measuring physiological and external parameters); data processing (enabled by built-in controllers); actuation (changing shape, temperature, etc.); energy supply (harnessing body heat, motion, light); and communication (via Bluetooth, NFC, conductive threads, optical fiber). The study highlights that such systems are capable of monitoring cardiovascular activity, physical movement, respiration, temperature, humidity, and pressure, as well as providing feedback through thermal action, color change, electrical stimulation, or vibration. The practical value of the research lies in laying the groundwork for the development of smart fabrics capable of passively stimulating muscle memory, which opens new possibilities in rehabilitation, personalized medicine, and smart living.*

Keywords: *smart textile, muscle memory, functionalized fibers, sensors, rehabilitation.*

Introduction

In the modern context of digital technology integration into everyday life, the rapid advancement of biomedical systems, and the growing interest in personalized healthcare solutions, smart textiles are emerging as a key direction in innovative textile manufacturing. These materials combine traditional textile properties with the functionalities of sensing, actuation, data processing, and communication, creating opportunities for clothing that not only serves protective or aesthetic purposes but also actively interacts with the user's body and the surrounding environment. The development of this technology is grounded in advances in materials science, nanotechnology, bioengineering, and electronics, which enable the creation of multilayer textile systems with integrated control, communication, and power supply components.

The relevance of the topic is driven by the need for wearable technologies capable of monitoring vital signs, adapting to the user's body, and delivering therapeutic effects in real time. Smart textiles are increasingly being adopted in medicine, sports rehabilitation, robotics, military applications, and domestic use. Thanks to modular architecture, customized design, and compatibility with biological systems, these fabrics form the basis of a new paradigm of interactive clothing – garments that not only respond to external stimuli but also analyze data, make decisions, and affect the user's body autonomously.

The potential of smart textiles in the passive stimulation of muscle memory remains underexplored in scientific literature. However, some aspects of the topic have been addressed in contemporary studies.

Literature Review

Significant contributions to this field have been made by researchers such as S. Allish et al. [1], who in their review highlight recent trends in smart textile development, emphasizing sensor integration and the capacity of these materials to interact with the human body. This lays a foundation for understanding how textiles can influence muscle activity. E. Frias-Miranda et al. [2] analyze the effects of motor learning through wearable resistance devices, which relates closely to the concept of passive muscle memory training. The research of G. Oatley and colleagues [4] confirms that smart textiles can impact not only physiological but also cognitive aspects of life quality, underscoring the multidisciplinary nature of the technology. The team led by P.T. Phan [5] demonstrates the potential use of artificial muscle fibers based on smart textiles, directly pointing to the possibility of both active and passive muscle engagement. Xu Z. et al. [10] in their study emphasize the importance of personalized smart solutions for sports medicine, which can support muscle activity without the user's active involvement.

In addition to academic sources, the study also relied on expert materials from contemporary online publications. For instance, articles from cottonmonk.com [3], ugent.be [8], and the University of Alberta's website [6] provide insights into the use of embedded sensors in textiles for muscle stimulation and improved motor function. These publications offer practical perspectives and reflect the growing interest in such innovations.

Despite the availability of literature on this topic, there is a clear lack of systematized material. Therefore, various methods of scientific cognition were used to analyze, group, and organize information in alignment with the subject of this research.

The aim of the article is to systematize the scientific and technical foundations for the development and functioning of smart textiles designed to perform biofunctional tasks in medical, rehabilitation, and domestic environments.

In order to achieve this goal, the study sets out the following tasks: (1) analyze the architecture of smart textiles, materials, and technologies used to produce functionalized fibers; (2) describe the functional capabilities of smart textiles as a cyber-physical system; (3) identify current development directions, technological potential, and promising application areas in the context of personalized therapy, sensory monitoring, and adaptive user interaction.

Research Results

The history of smart textiles dates back over a thousand years to when craftsmen began incorporating conductive materials into textile production by wrapping threads with metallic foils – typically gold or silver. These decorative threads were used in garments worn by European aristocracy, including dresses of Queen Elizabeth I [9]. In the second half of the 19th century, with the advent of electrical devices, engineers started integrating electricity into clothing, producing illuminated accessories, costumes, and headwear. During the 20th century, the development of electronics spurred experimentation with textiles embedded with light elements, sensors, and microprocessors. Notable examples include Harry Wainwright's animated LED jackets (1985) and the work of MIT researchers, who in the 1990s developed the first wearable computers and embroidery-based techniques for stitching electronic circuits directly into fabric. These milestones laid the foundation for today's smart textile systems [9].

S. Allish et al. [1] propose a conceptual classification of smart textiles into generations based on the level of functionality and integration of control technologies. Three generations of smart textiles are identified:

The first generation consists of passive smart textiles that perform only sensing functions. These fabrics can detect changes in the environment, such as ultraviolet radiation or humidity, but do not provide any active response. Examples include fabrics with optical sensors or plasma coatings [1];

The second generation includes active smart textiles that combine sensors with actuators, allowing them not only to register external stimuli but also to respond. Such textiles can change their color, shape, temperature, structure, or surface properties (hydrophobicity, thermoregulation, etc.). They already demonstrate adaptability to environmental conditions [2];

The third generation refers to ultra-smart textiles with the highest level of integration and autonomy. These systems function as complete cyber-physical complexes with embedded microcomputers capable of analyzing and storing data, predicting changes in conditions, and autonomously adapting. They essentially simulate the functioning of basic artificial intelligence within a textile environment. Examples include space suits, "intelligent" jackets with multimedia features, and wearable computers [2].

A development by researcher Bulchi Belay Etana from Ghent University involves a new generation of smart textile electrodes designed for comfortable and long-term monitoring of muscle activity [8]. This technology uses conductive threads embroidered directly into the fabric, ensuring close contact with the skin, high electrical conductivity, and wearing comfort.

Currently, based on the latest technological advancements, smart textiles can be defined as integrated systems in which functional components – sensors, actuators, computing units, and communication tools – are woven or embedded directly into the textile structure. Unlike traditional textiles, which serve only a passive role, smart textiles function as active interfaces between the user's body and the external environment, capable of detecting, processing, and transmitting physiological or mechanical signals [1].

Smart textiles are fundamentally capable of performing several key functions, which are outlined in Table 1.

Table 1. Functional components of smart textiles

Function	Description	Implementation examples	Current challenges
Sensors	detect physiological and external signals (temperature, motion, pressure)	heart rate monitoring, ECG, myograms, respiration, humidity, sound detection	signal variability; accuracy; data processing algorithms
Data processing	analyze and convert sensor signals into control commands	embedded microcontrollers or external processors	limited computing power of textiles; complexity of signal analysis
Actuators	respond to processed signals through motion, sound, shape or temperature changes	shape memory materials; thermoactive fibers	high cost; limited commercial applicability
Storage	store energy or data for autonomous operation	batteries; energy harvesters (body heat, motion, light)	integration; resistance to deformation and washing
Communication	transmit data between textile elements or with external devices	conductive threads; optical fiber; Bluetooth; NFC	connection reliability; protection from environmental factors

Note: systematized by the author based on source [1]

Let us take a closer look at how smart textiles function. The core components of textile structures are fibers, which provide sensitivity to external stimuli, flexibility, adaptability, and the ability to integrate functions without compromising the textile nature. Their diameters range from nanometers to millimeters, allowing control over the optical, electrical, and mechanical properties of the fabric. Authors Xu Z., Zhang C., Wang F. et al. classify smart fibers based on the source of their functionality into coated, intrinsically functional (pure), coaxial, and composite types. Specifically, coated fibers are produced by applying functional layers through methods such as in situ polymerization, electrodeposition, dip coating, and self-assembly. These layers provide sensing capabilities but require additional encapsulation to improve durability.

Pure fibers are made directly from functional materials such as graphene, MXenes, CNTs, or PEDOT. Forming these into macroscale, long, strong structures requires precise spinning conditions. For instance, liquid crystal spinning allows the fabrication of meters-long graphene fibers with high conductivity and mechanical strength. Xu et al. proposed a defect-engineering approach involving optimized spinning, thermal graphitization, and drawing, which resulted in fibers with a tensile strength of 1.78 ± 0.15 GPa and electrical conductivity reaching 200,000 $cm^2/V \cdot s$ [10].

From an architectural standpoint, modern smart textile systems are often built using a modular design, which is typically loosely coupled. This means that sensor components, computational modules, power sources, and feedback elements function autonomously but interactively. Such a configuration allows:

• reduced complexity in individual customization;

• easy scalability;

• adaptable functionality based on the task or user category [1].

These systems can be integrated into textiles in various ways, including weaving conductive threads, sewing sensor modules, or layering them between textile sheets. Their application often involves passive interaction with the user's body – for example, when the fabric is placed on the knees or back, stimulating tactile receptors or tracking movement without requiring active participation. This is especially important in cases of cognitive or motor impairments, where intentional motor activity is limited, making it essential for systems to operate autonomously, gently, and unobtrusively [1].

Thus, smart textiles function as interactive platforms that serve simultaneously as sensing environments, feedback mechanisms, and carriers of computational logic, offering vast potential for muscle memory stimulation, neuroplasticity, and continuous monitoring of the user's physiological state.

Functionalized fibers are the foundational elements of smart textiles, enabling the integration of sensing, actuation, energy, and communication functions directly into the textile medium. In general, functionalized fibers are classified by structural architecture and source of functionality. Based on structure, fibers are divided into:

• Monofilament fibers – made from a single material, usually based on conductive or functional polymers such as PEDOT, MXene, or graphene derivatives. These fibers exhibit inherent electrical or optical properties [2];

• Coaxial fibers – consist of an inner and outer layer, each serving a specific purpose such as conductivity, insulation, or mechanical protection. This structure effectively combines sensing sensitivity with durability [2];

• Composite fibers – formed by combining two or more functional materials within a single structure. Their functionality arises from the interaction between phases, such as a polymer matrix with nanofillers [2];

• Coated fibers – produced by applying a functional layer to the surface of a textile fiber. This may include conductive coatings, polymer films, or layers of active nanomaterials. The coating provides specific functionalities such as conductivity, hydrophobicity, or chemical sensitivity [2].

The manufacturing technologies for functionalized fibers include both modification of pre-existing fibers and direct formation during the production process. Table 2 summarizes the main technologies used in the production of smart fibers.

Table 2 – Technologies used in the production of smart fibers

Technology	Operating principle	Application features
Melt spinning	melting of polymer followed by fiber formation	scalable; used for thermoplastic polymers
Wet spinning	fiber precipitation from solution into a coagulation bath	suitable for polymers that do not melt when heated
Electrospinning	formation of nanofibers using an electrostatic method	creates nanostructures with high specific surface area
Coaxial spinning	simultaneous formation of fiber core and shell	enables the creation of multifunctional fiber architectures
Dip coating	immersion of fiber into a functional solution	simple method for surface functionalization
In situ polymerization	polymerization of a functional layer directly on the fiber	ensures stable adhesion of the coating
Self-assembly	construction of functional layers from molecular building blocks	allows control over layer thickness and structural order
Additive manufacturing	3D printing structures on the fiber surface or direct fiber printing	potential for creating microstructured fibers

Note: systematized by the author based on source [2]

The integration of such fibers into textile structures lays the groundwork for fabrics that actively respond to mechanical or biophysiological stimuli. A key advantage is the ability of smart fibers to be adapted for passive applications, where stimulation of muscular or sensory activity occurs without active user participation –

an essential feature for individuals with motor impairments or those undergoing rehabilitation [2].

A practical example of smart clothing development is demonstrated by a research team at the University of Alberta, which is carrying out an innovative project focused on the needs of end users – people with muscle weakness, mobility limitations, or a high risk of occupational injuries. Unlike traditional prototyping models, this team involves future users at the conceptual design stage, which allows for tailoring smart textiles to real-life scenarios, enhancing both their effectiveness and social acceptability [6].

Another notable example is the integration of smart fabrics with massaging devices proposed by Ihor Sarnov. His concept involves creating customized compression garments that incorporate mechanical stimulation to achieve multifactorial therapeutic effects. This is realized through patented technologies, including specially designed massage devices such as "Tetrakom," "Octopus," "Turtle," and "Star," which deliver multipoint tissue stimulation to activate proprioceptors, promote muscle relaxation, support lymphatic drainage, and enhance neurosensory integration. When combined with compression garments tailored via 3D scanning, these systems not only improve circulation and reduce pain but also activate soft tissue regeneration, enhance motor control, and lower neurophysiological stress. As a result, the proposed system merges textile innovation, biomechanical stimulation, and principles of personalized rehabilitation based on digital design and patented solutions.

It is important to note that the approach developed by Ihor Sarnov integrates not only advanced innovations but also traditional materials applied in novel therapeutic contexts. In particular, natural fibers such as wool and alpaca are used in the production of warming belts that deliver gentle, sustained heat to specific areas of the body. Wool, alpaca wool yarn, as well as natural cotton yarn and raw cotton fabric, possess intrinsic thermoregulatory and biocompatible properties, making them highly suitable for neuro-orthopedic applications. These materials contribute to the reduction of muscle stiffness, enhancement of microcirculation, and overall improvement of tissue vitality.

In parallel, state-of-the-art cooling technologies are incorporated into the neuro-orthotherapy framework. One notably effective solution involves the use of a specialized salt–water compound that, upon brief manual agitation, rapidly lowers its temperature to 0 °C or even −2 °C without the need for prior freezing. This immediate cooling effect provides rapid pain relief, suppresses inflammation, and limits hematoma formation – rendering it especially beneficial during the acute phase of injury or postoperative recovery. Both modalities – warming and cooling – are applied in a personalized and adaptive manner, enabling dynamic modulation of therapeutic effects in accordance with the patient's specific physiological requirements and stage of rehabilitation.

Modern smart textiles exhibit exceptional technological potential due to the combination of functional chemical-textile materials and miniaturized electronic technologies. This synergy enables the development of multifunctional solutions across healthcare, medicine, fashion, environmental protection, personal safety, robotics, and the Internet of Things. Technological advancement in this field centers on several key areas: electrical conductivity, flexibility, self-powering capabilities, biocompatibility, resistance to deformation and washing, and seamless integration into textile structures without compromising wearability [7].

The most promising directions are presented in Table 3.

According to an analytical forecast presented on the Cottonmonk platform [3], the future of memory technologies in textiles is defined by the integration of adaptive, autonomous, and intelligent functionalities into garment structures. Developments are expected to include self-healing fabrics capable of automatically repairing minor damage; interactive clothing that changes color or texture in response to external conditions; and smart apparel embedded with artificial intelligence algorithms that respond to the user's biometric parameters for health monitoring purposes. Memory technologies in clothing – particularly textiles with shape memory or temperature-reactive properties – are seen as a key factor in shaping a new generation of garments with high adaptability, ergonomic performance, and functional stability. These advancements are expected to significantly influence the sustainable development of the fashion industry and personalized manufacturing [3].

Table 3. Key application areas of smart textiles

Application area	Technological basis	Examples / Potential use
Self-powering	triboelectric, thermoelectric, photovoltaic, biochemical nanogenerators	smart gloves; sleep-monitoring bedding; energy-harvesting fibers
Artificial muscles	CNTs, graphene, shape-memory polymers, hydrogels, coiled fibers	soft robotics; rehabilitation; deformable textile structures
Liquid metal / MXene	high conductivity; stretchability; 3D-printed interfaces	stretchable electronics; EMI shielding; electrodes; conductive fibers
Strain / pressure sensors	piezoelectric, resistive, triboelectric sensors; MXene composites	physiological monitoring; gait analysis; speech translation; HMI systems
Thermal effect (Joule heating)	CNTs, AgNP, PEDOT:PSS, MXene, conductive polymers	medical thermotherapy; heated garments
EMI protection	silver, graphene, liquid metal, polypyrrole, multilayered structures	protection from electromagnetic radiation; safe wearable electronics
Hygiene and self-cleaning	hydrophobic, superhydrophobic, photocatalytic coatings	self-cleaning surfaces; stain resistance; preservation of garment appearance
Flexible electronics	textile electronics based on conductive fibers and nanostructures	reflective clothing; displays; augmented reality interfaces
Sustainability and recycling	biodegradable materials; circular design	environmental safety; reuse; regeneration of textile systems

Note: systematized by the author based on [7]

Conclusions

Smart textiles represent high-tech integrative systems that combine sensors, actuators, energy modules, communication tools, and computational components woven or embedded into the textile structure. These systems are based on functionalized fibers, classified by their architecture (monofilament, coaxial, composite, coated) and manufactured using technologies such as melt spinning, wet spinning, electrospinning, coaxial spinning, dip coating, in situ polymerization, self-assembly, and 3D printing. These processes offer scalability, flexibility, durability, and the ability to apply microstructured functional layers, enabling the creation of fibers with electrical, optical, chemical, or mechanical properties.

In terms of functionality, smart textiles perform five core tasks: sensing (measuring physiological and environmental parameters); data processing (via embedded controllers); actuation (modifying shape, temperature, etc.); energy harvesting (from body heat, motion, light); and communication (through Bluetooth, NFC, conductive threads, optical fiber). Their capabilities include monitoring cardiovascular activity, movement, respiration, temperature, humidity, and pressure, as well as providing feedback through thermal action, color change, electrical stimulation, or vibration.

Looking ahead, smart textiles are expected to evolve into platforms featuring artificial intelligence integration, adaptive behavior, self-repair, and energy autonomy. Key development directions include the creation of biocompatible, flexible, and renewable materials; the use of liquid metals, graphene, MXene, and triboelectric systems; the development of intelligent interfaces; and the implementation of personalized textile systems with multipurpose applications across healthcare, rehabilitation, protection, sports, and fashion.

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