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Smart E-textiles for Monitoring Health Parameters: Application in Clinical Medicine, Sports, and Social Sphere

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ABSTRACT

Modern scientific advancements promote the development of effective wearable biomedical technologies that will improve the quality of life and personalize approaches to prevention, therapy, and rehabilitation. E-textiles or smart clothing technology are attracting significant attention due to the opening of new horizons for monitoring medical and biological health indicators.

The review provides a critical analysis of possible modern applications of smart textiles for monitoring physiological health indicators. The article discusses the advantages, current limitations, and future prospects, as well as related research and development needed to implement practical solutions in the field of e-textiles. Smart clothing can be used to collect and process data on human body movement and bioelectric potentials or chemical signals in real time for various medical and everyday purposes. Wearable devices are a promising biomedical technology due to their innovative potential for modernizing healthcare, professional sports, and social sphere, providing continuous and non-invasive recording of physiological parameters.

Continuous scientific and technological progress in the development of materials with improved biocompatibility and durability, optimization of analytics based on artificial intelligence, and more accurate assessment of big biomedical data will accelerate the implementation of smart textiles and their integration with other digital applications for intelligent health monitoring. Further development of wearable e-textiles will contribute to improving both their diagnostic efficiency and the quality of life of users.

Keywords: e-textile; textile electrode; health monitoring; wearable technology; medical and biological indicators; smart clothing

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Интеллектуальная одежда для мониторинга медико-биологических показателей здоровья: применение в клинической медицине, спорте и социальной сфере

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РЕЗЮМЕ

Современные научные достижения стимулируют разработку эффективных носимых биомедицинских технологий, которые позволят повысить качество жизни и персонализировать подходы к профилактике, терапии и реабилитации. Технология интеллектуальной, или «умной, одежды» привлекает значительное научное и практическое внимание благодаря открытию новых горизонтов для мониторинга медико-биологических показателей здоровья.

В обзоре представлен обобщенный критический анализ современных возможностей использования интеллектуальной одежды для регистрации физиологических параметров организма и мониторинга здоровья. Обсуждаются преимущества, текущие ограничения и будущие перспективы, а также связанные с ними исследования и разработки, необходимые для реализации практических решений в области электронных текстильных изделий для медицинского мониторинга. Интеллектуальная одежда может использоваться для сбора и обработки данных о биомеханике человеческого тела, биопотенциалов или химических сигналов в режиме реального времени для различных медицинских и повседневных целей. Носимые устройства являются перспективной биомедицинской технологией из-за ее инновационного и многообещающего потенциала для модернизации системы здравоохранения, профессионального спорта и социальной сферы, обеспечивая непрерывную и неинвазивную регистрацию медико-биологических показателей состояния человека.

В перспективе научно-технологический прогресс в разработке материалов с улучшенной биосовместимостью и долговечностью, оптимизация аналитики и более точная оценка больших массивов биомедицинских данных позволят ускорить внедрение носимых электронных текстильных изделий и их интеграцию с другими цифровыми приложениями для интеллектуального мониторинга здоровья и достижения целевых стратегий профилактики и терапии. Дальнейшее развитие технологии «умной одежды» повысит ее диагностическую эффективность и в целом качество жизни пациентов и пользователей.

Ключевые слова: интеллектуальная одежда, мониторинг здоровья, носимые биомедицинские технологии, медико-биологические показатели, «умная одежда»

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INTRODUCTION

Due to the heterogeneity and large volume of recorded medical and biological information, the need has gradually emerged to develop and implement advanced, intelligent and at the same time accessible technologies capable of collecting, storing, analyzing,

and transmitting data [1]. Among such innovative medical technologies are wearable systems for monitoring physiological indicators, implemented through interdisciplinary solutions and scientific and technological integration of digital healthcare, microelectronics, wireless communications, analytics, and textile production [2, 3].

Adding electrodes and sensors to textiles and clothing is a promising way to record physiological parameters [4]. This technology is gaining recognition for its potential in diagnostics and long-term monitoring of daily activities and recording the dynamics of various vital signs. Due to scientific research and technological advances, wearable electronics are now becoming a sought-after product in the healthcare and sports medicine sectors. Mass production and integration of sensors into textiles open up new possibilities for monitoring health, fitness, and overall performance in clinical settings, daily life, and sports training [5].

Previously, sensors for recording medical and biological signals were placed directly on the body or in special compartments in textiles. The modern concept of wearable biomedical technologies “Wearable 2.0” provides complete integration of wearable electronics into clothing. In the scientific community, such systems are known as Smart clothing (SC), Intelligent textile, Electronic textiles (e-Textiles) or Wearable textile electrodes [6–8].

The aim of this review was to critically and constructively analyze the results of research to determine the potential of using Smart Clothing for monitoring and recording biomedical parameters. The advantages, current limitations, and future opportunities are discussed, as well as the related research and development required to implement practical solutions in the field of e-Textiles and their application in clinical medicine.

ALGORITHM FOR WORKING WITH SOURCES: SEARCHING AND SELECTING PUBLICATIONS

To achieve the stated goal and prepare the review, a search for publications was performed in the PubMed, Scopus, and RSCI databases using search queries and keywords. The systematic search included articles published over the past 10 years (2015–2025). The query and analysis language was English. In particular, the following keywords and their combinations were used: Smart clothing, e-Textile, Wearable technology,

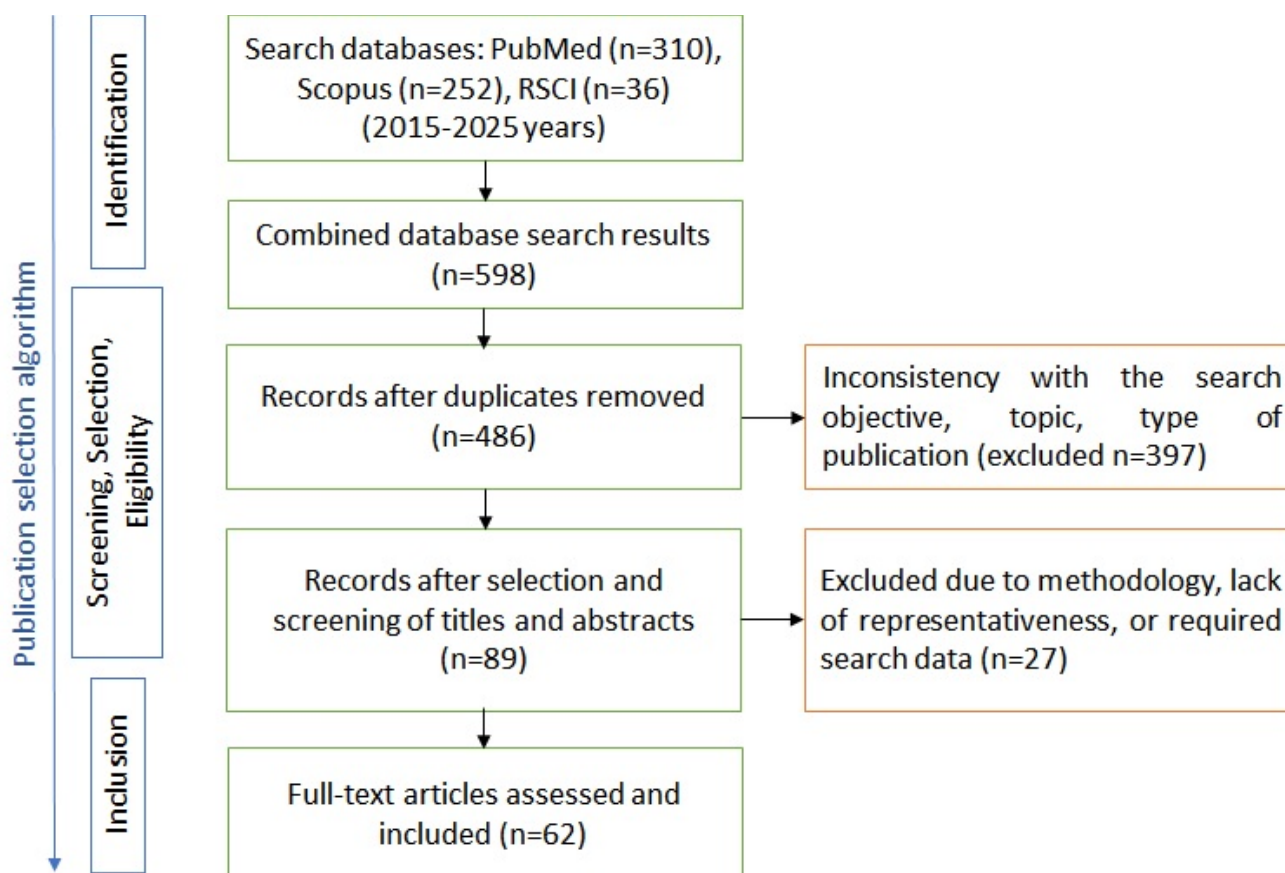


Fig 1. Flow chart for selecting publications

Textile electrode, Smart textile technology, Wearable electronic devices, Biosensors, Health monitoring, Digital health. The review was guided by the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses and relied on the search methods described in the RELISH consortium. To expand the systematic search, the operators AND/OR were used to combine keywords. According to the stated search objective, abstracts of reports, meeting minutes, books, conference materials, and clinical cases were not used to analyze the results. The generalized analysis of the technology application included publications of the research results that adequately presented the initial data – characteristics and parameters of the development and use of SC for non-invasive recording and monitoring of medical and biological indicators of the human physiological state. At the initial stage, 598 articles were identified across all databases. The selection was performed based on titles and abstracts. After removing duplicates and publications that did not correspond to the topic and aim of the study, data were obtained, and full texts of 62 articles were analyzed in accordance with their methodology, results, and conclusions (Fig. 1). To comprehensively describe the possibilities of using SC, identify the advantages, limitations, and future prospects of the technology, and expand the critical view of the problem posed, the general analysis and references include data from original studies, technological developments, validation and observational clinical trials, meta-analyses, and research in related areas.

DEVELOPMENT AND APPLICATION AREAS OF SMART CLOTHING

The development of flexible, stretchable electrodes is a key component of electronic functional wearable textiles capable of sensing, transmitting, and analyzing data. Most clothing materials worn by humans every day are made of flexible textile fabrics consisting of one or more types of natural or artificial fibers, with the main requirements for them being the ability to provide comfort and physiological, including sensory, properties for the consumer [9, 10]. At the same time, the fabrics must be wear-resistant during cleaning (washing) and repeated use of clothing. However, the implementation of such requirements is significantly complicated when rigid or fragile electronic systems are integrated with textile materials, which is the main current limitation in the design of SC. Therefore, the general trend in the development of prototypes of

electronic textiles is aimed at solving the problem of minimal disruption to user comfort when wearing such clothing and the ability to detach the electronic components. Another challenge is the precise positioning of the appropriate electrodes over the target area in order to perceive biosignals with the highest quality and without interference and artifacts [11, 12].

Potential areas of application of SC can be divided into three groups (Fig. 2): for clinical use in healthcare (the main direction) – registration and monitoring of physiological parameters, medical conditions, dynamics of the therapeutic process or rehabilitation treatment; application in sports – monitoring the physical status and performance, expanding the rehabilitation potential of athletes; for the social sphere – to facilitate any non-professional and everyday activity of patients, users, and especially persons with disabilities [13, 14]. Equally, electronic textile products can be used in the above-mentioned sectors, depending on their basic functionality and consumer choice (which determines a more pronounced demand for the technology from the fitness/sports and digital medicine industries). At the present stage, the focus is shifting towards the design and development of technically advanced high-performance SC, which is not only comfortable and interactive, but also offers significant added value in terms of functionality. E-Textiles are a promising asset because technologically advanced prototypes are adaptable and have the potential to be used in both the medical or sports sectors as well as in the social area due to the global population aging and the growing number of people with disabilities [15, 16].

TYPES OF SENSORS AND RECORDED BIOMEDICAL SIGNALS

E-Textiles require electronic components to interact with stimuli, such as mechanical, electrical, or chemical signals of the body's state. Various SC characteristics vary depending on the integrated electronics or technology platform, which creates new functionality for traditional clothing and provides additional value [17, 18]. It is likely that the most effective prototypes of e-Textiles being developed will eventually scale up into commercial products and significantly increase the market size, especially in the healthcare and sports sectors. The market for wearable e-Textiles is currently projected to grow at a rate of over \$1 billion per year [5, 19]. Over the past 5–10 years, advances in nanotechnology and manufacturing

techniques have led to tremendous changes in the field of flexible electronics and the development of SC with the inclusion of additional functions to increase their commercial value, increasing the demand for the development of systems aimed at monitoring biomedical parameters of the human body's state [20–23].

Since the early days of SC development, various ways of integrating electronics into textiles have been demonstrated [24]. The first-generation e-Textiles included a rigid component (electronic device, electrode) attached or sewn onto the surface of the garment or embedded in special compartments or pockets. Such products are typically larger in size

and less durable under constant use and maintenance. Subsequent development and manufacturing transformation have shifted the focus to more user-friendly e-Textiles with wearable technologies integrated into the garment itself. In the second-generation SC, conductive threads and biomedical sensors are actually woven into the textile structure to produce fully functional wearable e-Textiles. Thus, modern prototypes of smart textiles are characterized by full integration of textile and electrodes [25]. In the future, this technology will increasingly develop towards the Internet of Things (IoT) and deep integration with artificial intelligence, human-machine interfaces, and cloud technologies [7, 26].

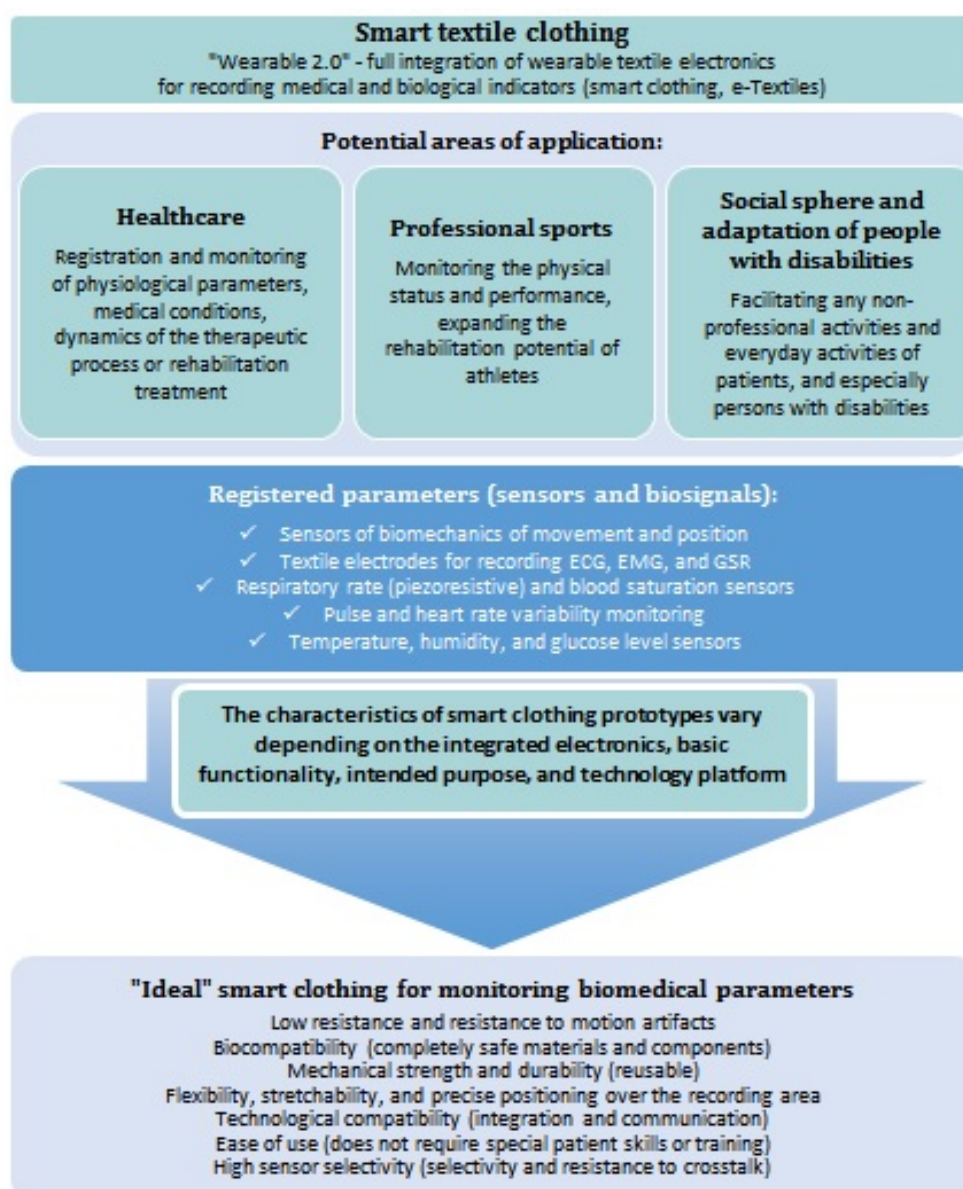


Fig. 2. Smart e-Textile technology for monitoring biomedical parameters

Sensors that can perceive medical and biological signals are conventionally classified into physical, electrical or chemical depending on the application purposes [27]. Various types of specialized electrodes are used to record physiological parameters, which can be either non-invasive – placed on the skin surface, or invasive. At the present stage, textile fabrics serve as a basic platform for integrating various electronic subsystems into them or on them. The quality and reliability of the recorded signal and the sensor itself integrated into the SC depend on the constituent components of the sensor unit [28, 29]. Sensors vary significantly in their intended purpose and can be, for example, biomechanical, temperature or biopotential sensors. Thus, well-known motion and position sensors are an accelerometer, magnetometer, and gyroscope (separately or in combination in one unit). Electrical potentials of cardiomyocytes and heart rate variability are among the most common biosignals recorded for monitoring human health in clinical practice, as well as in sports medicine and social area [30, 31]. Classic silver chloride-based hydrogel electrodes are not suitable for long-term wear, so dry textile-based electrodes have been developed for wearable sensor units. Such sensors are mainly manufactured by applying conductive ink (paste) to textiles using industrial or laboratory printing [32, 33]. The materials and manufacturing process of electrodes for recording electrical biopotentials of muscles and indicating muscle activation patterns (EMG) correspond to those described for ECG recording. Piezoresistive sensors sensitive to changes in resistance and capacitance integrated into textiles are used for real-time respiratory rate monitoring [34, 35]. Prototypes of SC with sensors for temperature and humidity changes or recording blood oxygen saturation and glucose levels are also being developed [14, 36, 37]. Such wearable electronics allow for monitoring health of patients and their clinical status over a long period of time. Therefore, e-Textiles for monitoring physiological signals can be an effective tool for early detection and monitoring of cardiovascular diseases, cerebrovascular events, sleep disorders, neurodegenerative and psychophysiological disorders, as well as for monitoring the rehabilitation process and daily activity [38–42], which determines broad opportunities for the application of the technology in clinical medicine, sports, and social sphere.

PROSPECTS OF DIGITAL MEDICINE

With technological advances and the need to improve the quality of healthcare services while reducing existing

costs, a great amount of generated biomedical data has high added value in areas such as clinical decision-making support, chronic process monitoring, anti-aging and personalized medicine, cognitive well-being, staff productivity optimization, and multi-level management in healthcare. With the global shift to personalized, preventive, and evidence-based models of healthcare delivery in clinical practice, there is a growing demand for the use of safe and long-term monitoring, analysis, and storage of large volumes of information. Wearable technologies open new horizons and are recognized as a critical element of digital medicine, as they provide advantages for the cost-effective and safe use of modern medical technologies [43–46].

Systems developed as clothing with integrated electronics offer technology capable of non-invasive tracking and analysis of physiological biopotentials and biomechanical data, which opens up additional opportunities for improving preventive medicine, early diagnosis, and timely correction of physical and mental health [47, 48]. In particular, wearable technologies with integrated motion sensors and surface EMG can potentially be used in patients with motor disorders, neuromuscular and musculoskeletal dysfunction, during rehabilitation after acute cerebrovascular events, fibromyalgia, multiple sclerosis, neurodegenerative diseases or sleep – wake cycle disorders, and in general for monitoring daily activity. Electronic textiles sensitive to chemicals, electrophysiological skin response, and biopotentials open up prospects for continuous recording of vital signs for the early detection of pathological changes and effective monitoring of a wide range of chronic and age-associated diseases, including cardiovascular, metabolic, and psychophysiological disorders [1, 49–55].

Thus, modern technologies in healthcare, including wearable devices, can become a key element of telemedicine, remote monitoring, and rehabilitation treatment of patients, providing opportunities for personalized medical services outside of traditional clinical settings [56–58]. Moreover, the increasing prevalence of chronic diseases and global population aging only increase the need for the implementation of innovative technologies to improve the quality of medical care and direct the transformation of healthcare towards the widespread use and accelerated clinical testing of Smart clothing [59, 60].

SYSTEMATIC ANALYSIS OF TECHNOLOGY

The systematic review demonstrates three main directions in the research of SC for monitoring

biomedical parameters: technical development of prototype devices, validation trials for widespread use by clinicians and specialized researchers who require valid and reliable measurements, and observational clinical studies [3, 21, 25, 34, 61–63].

Technological Features and Methods of Manufacturing

Due to their high electrical conductivity and biocompatibility, metals (silver or copper) are often used in SC prototyping to manufacture conductive elements and sensors. Although there are many types of fabrics that can be technologically combined with metals, their durability during repeated use and maintenance of products remains a limitation and requires further scientific development and practical improvement [64, 65]. Polystyrene sulfonate, polypyrrole, and polyaniline belong to the class of organic polymers that, due to the peculiarities of their chemical structure, are electrically conductive and therefore are of interest for the development of electronic textiles. The main limitations of such polymers are their low mechanical stability and poor flexibility, which potentiates the search for composites with other elastic polymers to increase strength and reduce brittleness [66, 67]. Carbon-based materials are in demand in the field of biosensors due to their biocompatibility, flexibility, thermal and chemical stability. Graphite or graphene can be produced in large quantities and are relatively inexpensive, so commercialization of such electrodes for wearable biomedical technologies is quite feasible, but improvements in developments are required to ensure a uniform, stable coating of the material on textiles [68, 69].

Simple and inexpensive methods used to fabricate SC include dyeing, roll-to-roll coating, spray-coating, and dip-coating. In particular, in observational clinical studies and evaluation of electronic textiles prototypes, the use of such methods for depositing carbon conductive materials showed that e-Textiles retained mechanical strength and stability after 20–30 washing cycles and allowed for recording high-quality biosignals [70, 71]. Modern technologies using computer graphics, electrospinning methods, or industrial printing make mass production of SC possible. Electrospinning produces ultra-thin nanofibers with a diameter from several micrometers to hundreds of nanometers, which demonstrate good mechanical strength and high specific area, and the resulting textile electrodes have a porous

structure, which improves air permeability, electrical conductivity, and adhesion to the skin required to obtain high-quality EMG and ECG signals. In laboratory printing, various types of conductive inks are tested on textiles, including metal nanoparticles, conductive polymers, and carbon materials. It is worth noting that the conductive materials used for printing must not only firmly bond to the fabric surface, but also be stable and not lose conductivity when stretched and repeatedly used in wearable technology [61, 72–75].

Advantages of Technology

1. Smart textile solutions provide a simple, convenient, and understandable platform, while containing non-invasive sensors.
2. Increased compliance – integration of electronic systems into clothing promotes patient adherence and better implementation of diagnostic recommendations.
3. Multifunctionality – several sensors can be embedded into one platform (garment) in different target areas, which eliminates the use of several separate devices and allows for measuring a wide range of signals.
4. Reusable dry textile electrodes as part of the SC are more cost-effective for long-term monitoring.
5. In the future, invisible and seamless integration of miniature electronic components will ensure a close and positioned contact of biosensors with the recording area, which will reduce measurement errors caused by cross-talk, displacement, and discomfort of rigid and large sensors.

Identified Limitations of the Technology

Despite the interest of basic and applied research in the development and scaling of SC for biomedical purposes, the analysis revealed a number of current limitations.

1. Decreased signal quality and accuracy depending on environmental conditions and external interference, sampling frequency, contact quality.
2. Lack of uniform standards for the production process, methodology, and legislation in the development and validation of products.
3. Energy efficiency – the need for a reusable energy source and integration with batteries, which negatively affect the size, comfort, and flexibility of products.
4. Limited contact area and difficulty in accurately positioning sensors without displacement, high sensitivity of sensors to motion artifacts.
5. Comfort and safety: ensuring long-term use without discomfort or irritation.

6. Wear resistance and limited service life.

7. The need for specialists to analyze large volumes of recorded information and identify suitable data for transferring scientific results into clinical practice, as well as systematic validation of products.

8. Ethical and privacy issues – strong encryption and secure solutions to protect patient information.

Prospects and Future Possibilities of the Technology

Validation studies and clinical trials of prototypes have identified the following characteristics of an “ideal” e-Textile product for recording medical and biological parameters [2, 9, 11, 27, 33, 68, 76–78]: biocompatibility; flexibility, and stretchability with precise positioning over the recording area; resistance to motion artifacts; mechanical strength; ease of use for the patient; technological compatibility, integration, and communication with other equipment; selectivity of integrated biosensors.

The solution to the described problems and limitations requires further research and the creation of additional opportunities for improving the SC. To improve the quality of recorded biosignals, reliability, durability, and the level of integration of wearable technologies, continuous development of new materials and components is required. The interaction of electronic textiles with other innovative technologies adds new functions and contributes to the development of the concept of next-level wearable biomedical devices in the field of SC personalization. Thus, the use of AI tools and digital technologies to improve analysis algorithms will allow for the development of personalized diagnostic and treatment plans, predicting the progress of rehabilitation or the training process [79–81]. In general, with an interdisciplinary approach and the simultaneous participation of various stakeholders, including technology developers and manufacturers, health and professional sports experts, as well as end users and government regulation, it is possible to effectively transform scientific achievements in the field of electronic textiles into consumer-oriented, economically in-demand, and sustainable solutions. Therefore, additional efforts to create industry-wide standards and optimize validation and implementation processes will play a decisive role in the development of wearable biomedical technologies.

CONCLUSION

Current advances in the development of wearable textile electrodes demonstrate a great potential

of the technology for non-invasive monitoring of physiological parameters and subsequent effective and widespread implementation in practical healthcare for the prevention, therapy, and rehabilitation. However, further research is needed to overcome a number of problems and current limitations with maximum implementation of the potential. New steps in the further scientific and technical development of the technology include not only the development of new materials and components, but also systematic validation, improvement of manufacturing processes, and increased accessibility for users and patients. Future research should focus on the development of materials with improved biocompatibility and durability, optimization of analytics, and more accurate evaluation of large arrays of biomedical data. A comprehensive consideration of these areas will accelerate the implementation of e-Textiles and their integration with other digital applications for intelligent health monitoring, which will generally improve the diagnostic efficiency of the technology and the quality of life of patients and users in real conditions.

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