Review Article

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Smart technologies and textiles and their potential use and application in the care and support of elderly individuals: A systematic review

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Abstract: Demographic change is causing society to age. At the same time, technological progress is changing the way ageing individuals are cared for and medically treated. Several smart wearables and garments have recently been developed for this purpose. Based on previous research, we see a research gap in the use of smart clothing in the care and support of elderly people, especially with regard to concrete application potentials and example products. The aim of this study was to provide an overview of the latest studies and developments in smart clothing with a focus on usability and acceptance for an elderly individuals. A systematic literature search was performed in five databases using a predefined set of keyword. A total of 169 articles published between 1/2000 and 2/2023 were identified and assessed. The literature search followed a previously prepared research protocol according to the criteria of a systematic literature search. The research field of smart clothing is expanding with smart shirts being a major focus; however other products are also being investigated, each with specific capabilities. In particular, vital parameters are constantly optimized; representative products are described and assessed according to their potential applicability to elderly people. The future applications of smart clothing in health care are promising. Many studies on basic applications of smart textiles have been done, and some studies have already involved older people. Furthermore, newly developed suggestions for possible categorizations of smart wearables as well as smart clothing as a subtype are presented based on the researched literature. We found an overall positive impression of the development and application of smart clothing, especially in geriatric settings. However, aspects such as data collection, skin compatibility, wearing comfort, and integration of geriatric factors into known acceptance models need further investigation. Over the last two decades, there have been many developments in the field of smart clothing. For the care and support of elderly people, smart clothing is an important development with great potential. Continued advancement in these products is needed to adequately address the special needs of older people.

Keywords: smart textiles, wearable technology, technology acceptance, smart shirt, elderly care, vital sign monitoring, geriatrics

1 Introduction

Recent developments in (micro)technology and its related sectors offer great opportunities for a wide range of applications. Companies (*e.g.*, Google, Apple), developers, universities, and research institutes are allocating considerable resources, effort, and time into developing new smart technology products, including smart wearables and smart clothing. These products are suitable not only for military and gaming purposes but also for applications in medicine and health. More recently, the older adult population has been identified as a target population for electronic appliances [1–3]. This focus is particularly important, as in recent decades, developed countries have undergone demographic changes leading towards an ageing society [4]. The steady

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ageing of the population will continue to increase in the medium term, resulting in ever longer periods of needing care and assistance for an increasing number of elderly citizens [4,5]. The United Nations estimates that the proportion of elderly individuals in the global population will triple by 2050 and describes this trend as a major challenge to societies worldwide. As the need for additional assistance in multiple forms becomes increasingly necessary for older citizens, the question of how to adequately care for these individuals arises [4]. Shortcomings in elderly care can arise in the home, in an inpatient environment, and in long-term care provided by family doctors. Assistive technology can and should complement care for elderly individuals [6–8].

The use of smart technologies, including smart clothing, is conceivable for various application scenarios. Such innovations can play an important role in long-term and preventive care. For example, patients who live far away from medical care providers or who have limited access can benefit from distance monitoring with rapid data transmission.

In addition, new technologies can enable inpatient and nursing facilities to detect critical conditions more quickly and react accordingly [9–11]. Some authors even suggest combining smart clothing with smart home environments to provide "all-round care" [12,13].

Smart clothes and textiles could be a new solution for monitoring vitals, such as offering a reliable and simple alternative to monitoring during sleep (*e.g.*, polysomnography or sleep apnoea detection) [14–16].

The special circumstances of older adults must be taken into account to tailor age-specific technologies in a user-friendly manner. These needs include an increased tendency to fall, the need for care and supervision, cognitive performance deficits, increased multimorbidity, and frailty with existing physical weakness [17,18]. Another important consideration is ensuring that such new technology will be accepted by the elderly population, whose preferences may differ considerably from those of younger populations.

This article pursues an overarching aim by examining smart clothing in terms of its potential for application in the care and support of older people. This is achieved *via* three aspects:

1) the latest technological developments in the smart textile sector are collected and presented,
2) potential and existing examples of smart shirts and garments are presented, and
3) specific situations in the geriatric context to identify application needs and opportunities are described.

Previous work is examined in terms of its focus and is listed below. Many studies deal with potential technical functions as well as the possibilities of data collection. Some works from the field of gerontotechnology and sociology already deal with the more concrete applicability with elderly people, this is where our work shall tie in.

2 Methods

2.1 Literature selection process

This review was prepared according to the criteria for systematic reviews of the literature following PRISMA checklist as well as on the basis of a research protocol of RefHunter [19–23]. To avoid potential bias in the search and review of the literature as much as possible, we conducted the review according to a previously formulated protocol [23]. Here, we formulated the overarching research question of the application potential of smart clothing for the care and support of the elderly individuals, which was presented using current studies and specific product examples.

We formulated the selection (inclusion and exclusion) criteria listed in the next paragraphs as well as a search strategy, the following databases were considered for this: ScienceDirect (Elsevier), PubMed, the Cochrane Library, the Institute of Electrical and Electronics Engineers (IEEE Xplore), and Google Scholar. The databases listed were selected primarily because of their size in terms of content and the fact that the literature they contain is largely freely accessible, so that it is possible to reconstruct the data collected without restriction. Furthermore, databases were selected because they deal in particular with medical, technological, and overlapping topics. They were used to search for articles published between January 2000 and February 2023. The following keywords and their combinations were used as search terms: *smart textiles, wearable technology, technology acceptance, elderly people, user acceptance, smart shirt, elderly care, smart clothing, vital sign monitoring, and geriatrics.* The MeSH terms *health services for the aged* and *smart materials* were also used for the search in PubMed (Table 1). To give a concrete view of available products and current developments in addition to the systematic literature review, corresponding manufacturers and products were evaluated by their relevance. For this purpose, the manufacturers' websites and previously published papers on these products were taken into account. Table 2 provides an overview of current products, including web addresses and scientific references.

The following inclusion and exclusion criteria were developed before the research was undertaken:

Table 1: Tabular overview of the search terms used in the databases

Search components	Keywords	PubMed*	The Cochrane Library	Google Scholar	IEEE Xplore	ScienceDirect
Patient groups: geriatric patients/elderly	Elderly	✓	X	X	✓	✓
	Elderly people	✓	✓	✓	✓	✓
	Geriatrics	✓	✓	✓	✓	✓
	Elderly care	✓	✓	✓	✓	✓
Intervention: smart shirt/clothing/textiles	Smart shirt	✓	✓	✓	✓	✓
	Smart clothing	✓	✓	✓	✓	✓
	Smart textiles	✓	✓	X	✓	✓
	Wearable technology	✓	✓	X	X	✓
Outcome: acceptance, comfort, and valid data collection	Acceptance	✓	✓	✓	X	✓
	User acceptance	✓	✓	✓	X	✓
Setting: home environment, clinical application, and research laboratories	Vital sign monitoring	✓	✓	✓	✓	✓

*MeSH terms *health services for the aged* and *smart materials* were also used for the search in PubMed.

Inclusion criteria:
- Publications and articles published between January 2000 and February 2023
- Publications and articles that were written or available in either the English or German.

The period after 2000 was chosen because the development of intelligent textiles only began to become relevant in that year. In 2001, Tao [24] published a review of the developments, materials, and initial products related to intelligent and functional textiles going back to 1965, when a heat-insulating garment was developed by Mavelous and Desy.

The preliminary search (Identification) resulted in a total number of 807 articles. By omitting duplicates and irrelevant abstracts, 211 full-text articles were identified (Eligibility and Screening). After a careful analysis of the content of each reference using respective checklists [25], a final total of 122 articles and competing sources were included in the systematic review. To supplement some further aspects of this work, 47 additional references were used in the elaboration of this article (Inclusion). As shown in Figure 1, a modified PRISMA flow diagram was used to illustrate the selection process [26].

Data were to be collected from the literature sources in the form of: data on relevant references, using not only research literature but also other sources of information (books, websites), data on the most important results and statements of the references with the question of a common intersection, data on already existing example products that could have relevance for answering the research question, data on the type of references using a qualitative, narrative presentation of the studies as well as data on open research questions that can possibly be identified with our work.

Based on the available literature and additional sources, such as manufacturers' websites and online statistics, we developed a proposal of categories (Figure 2) and a tabular overview (Table 2) of products relevant to our research question. An endnote database (Clarivate, UK) was created and used to prepare and organize the references.

2.2 Definitions of terms

In the current research literature and manufacturers' specifications, a variety of definitions are used to determine smart wearable products, and no definitive terms clearly distinguish between current product varieties. Therefore, we use the following terms throughout the article. *Smart wearables* are a superordinate designation that refers to any device that can be worn on the body but is not implanted into the body. These include smart clothes (as a textile variation) and various other products, such as glasses, watches, measuring devices, wristbands, and headbands. The designation *smart clothing* (smart textiles, smart clothes, and smart garments were also used) refers to any garment with more advanced technical or technological features that enable the garment to perform new functions. These features may include light-emitting diodes (LED) lighting, heat transfer or storage, signal transmission, and complex sensor functions.

Table 2: Overview of current developments of smart clothes (example products)

Product	Manufacturer	Main function/property	Connectivity	URL/Weblink	Scientific reference
Enflux Motion Capture Clothing	Enflux, Inc., Sherman Oaks, CA 91403 U.S.A.	Motion capture	Windows applications (Blender, Unity)	https://www.getenflux.com/	Comparing heading estimates from multiple wearable inertial and magnetic sensors mounted on lower limbs [140]
Smartsuit Pro	Rokoko	Motion capture	Windows10, Mac OS X Unity5, Unreal Engine, Motion Builder	https://www.rokoko.com/en/products/smartsuit-pro	Investigation of wearable motion capture system towards biomechanical modeling [141]
Athos Training System	Athos	Athlete monitoring	iOS App	https://www.liveathos.com/	Validity and reliability of surface electromyography measurements from a wearable athlete performance system [142]
Mocapsuit & Mocapsuit-SE Cobra glove Bioman+	King's Metal Fiber Technologies & AiQ Synertial	Motion capture	n.a.	http://www.kingsmetalfiber.com/aiq, http://www.aiqsmartclothing.com/	n.a.
Hitoe performance fabric	Toray	Wearable biosensor fabric	n.a.	https://www.hitoe-toray.com/	n.a.
Neuronmocap	Noitom	Motion capture	n.a.	https://neuronmocap.com/ja	n.a.
Vector, Clearsky, Playertek	Catapult	Athlete monitoring	Apple watch and more	https://www.catapultsports.com/	n.a.
Siren Socks TM	Siren	Foot temperature monitoring	Companion app and/or text message service	https://siren.care/	n.a.
Ombra Smart Bra	OM Signal	HR and respiratory rate monitoring	n.a.	https://www.wareable.com/smart-clothing/omsignal-smartbra-unveiled-ces-2104	n.a.
Sensoria Artificial Intelligence Sportswear	Sensoria	Athlete monitoring	n.a.	http://www.sensoriafitness.com/	n.a.
Hexoskin	Carre Technologies Inc. (Hexoskin)©	Health monitoring	n.a.	https://www.hexoskin.com/	Clinical decision support for early detection of prediabetes and type 2 diabetes mellitus using wearable technology [111] Late breaking abstract – validation of hexoskin biometric technology to monitor ventilatory responses at rest and during exercise in COPD [109] The accuracy of VT measured with a smart shirt during tasks of daily living in healthy subjects: cross-sectional study, October 2021, Mannée *et al.* [143]

(Continued)

Table 2: *Continued*

Product	Manufacturer	Main function/property	Connectivity	URL/Weblink	Scientific reference
Owlet Smart Sock	Owlet Baby Care	Baby monitoring	n.a.	https://owletcare.com/	Initial experience and usage patterns with the owlet smart sock monitor in 47,495 newborns [144]
SUPA Powered Sports Bra	SUPA	HR monitoring	n.a.	https://shop.supa.ai/products/supa-powered-bra-supa-reactor	n.a.
VisionBody Power Suit	VisionBody	EMS training	VisionBody Pad with software	http://visionbodyasia.com/	n.a.
Teslasuit	VR Electronics	Motion capture Vital sign monitoring Virtual and augmented reality	Companion software	https://teslasuit.io/	n.a.
Vexatec	Vexatec AG	Athlete monitoring	n.a.	http://www.vexatec.com/	n.a.
X10X, X10Y	L.I.F.E. Italia srl	Health monitoring Sleep monitoring	Companion app	https://www.x10y.com/	n.a.
E-skin	Xenoma (Tokyo, Japan)	Motion capture Health monitoring under development	Companion software	https://xenoma.com/	n.a.
Smart fabric belly band and baby band	Drexel Center for Functional Fabrics and Drexel Wireless Systems Lab	Uterine activity and infant respiration during pregnancy	n.a.	https://drexel.edu/functional-fabrics/research/projects/smart-fabric-bellyband/	On implementing an unconventional infant vital signs monitor with passive RFID tags, Vora *et al.* [145], On the use of RFID for continuous biomedical monitoring, Mongan *et al.* [114]
Soft Robotic Assistive Glove	Advanced Robotics Center (Evolution Innovation Lab) at the National University of Singapore	Soft robotics in rehabilitation: movement support and performance of passive movements of the impaired body region	n.a.	https://www.rayelab.org/soft-robotics-in-healthcare	Low *et al.*, Effect of a soft robotic sock device on lower extremity rehabilitation following stroke: a preliminary clinical study with focus on deep vein thrombosis prevention [117]
Soft Robotic Sock and ARMAS Shoulder					The exosleeve: a soft robotic exoskeleton for assisting in activities of daily living, 2018 [118]
Smart sleeve	Xu *et al.*, University of Science and Technology of China	Human activity recognition (HAR)	Companion software/dataset available	n.a.	Xu *et al.*, Smart-sleeve: a wearable textile pressure sensor array for human activity recognition, 10.3390/s22051702, February [120]
Ambiotex smart shirt	Schams *et al.*, German Sport University Cologne	HRV	n.a.	n.a.	Validation of a smart shirt for HR variability measurements at rest and during exercise, Schams *et al.* [121]

(Continued)

Table 2: *Continued*

Product	Manufacturer	Main function/property	Connectivity	URL/Weblink	Scientific reference
OncoSmartShirt	Steen-Olsen *et al.*, University Hospital of Copenhagen, Copenhagen, Denmark	Electrocardiogram, thoracic and abdominal respiration, temperature	n.a.	n.a.	Feasibility of monitoring patients who have cancer with a smart T-shirt: protocol for the OncoSmartShirt Study, 2022 [122]
NEVERMIND System	Carli *et al.*, National Centre for Suicide Research and Prevention of Mental Ill-Health, Karolinska Institutet, Stockholm, Sweden	Vital sign monitoring	Companion app/ software	n.a.	The NEVERMIND e-health system in the treatment of depressive symptoms among patients with severe somatic conditions: a multicenter, pragmatic randomized controlled trial, DOI:10.1016/ j.eclinm.2022.101423 [123]
DAid smart shirt	Riga Technical University and Riga Stradins University, Latvia	Motion capture, HAR	n.a.	n.a.	Improving the recovery of patients with subacromial pain syndrome with the DAid smart textile shirt [124]
Tyme Wear smart shirt	Gouw *et al.*, Western Colorado University, Gunnison, USA	Detection of personalized ventilatory thresholds	n.a.	n.a.	Is the Tyme wear smart shirt reliable and valid at detecting personalized ventilatory thresholds in recreationally active individuals? [125]
Photonic Smart Garment	Avellar t al., Federal University of Espírito Santo, Brazil	Movement analysis, artificial intelligence	n.a.	n.a.	Avellar *et al.*, AI-enabled photonic smart garment for movement analysis [126]

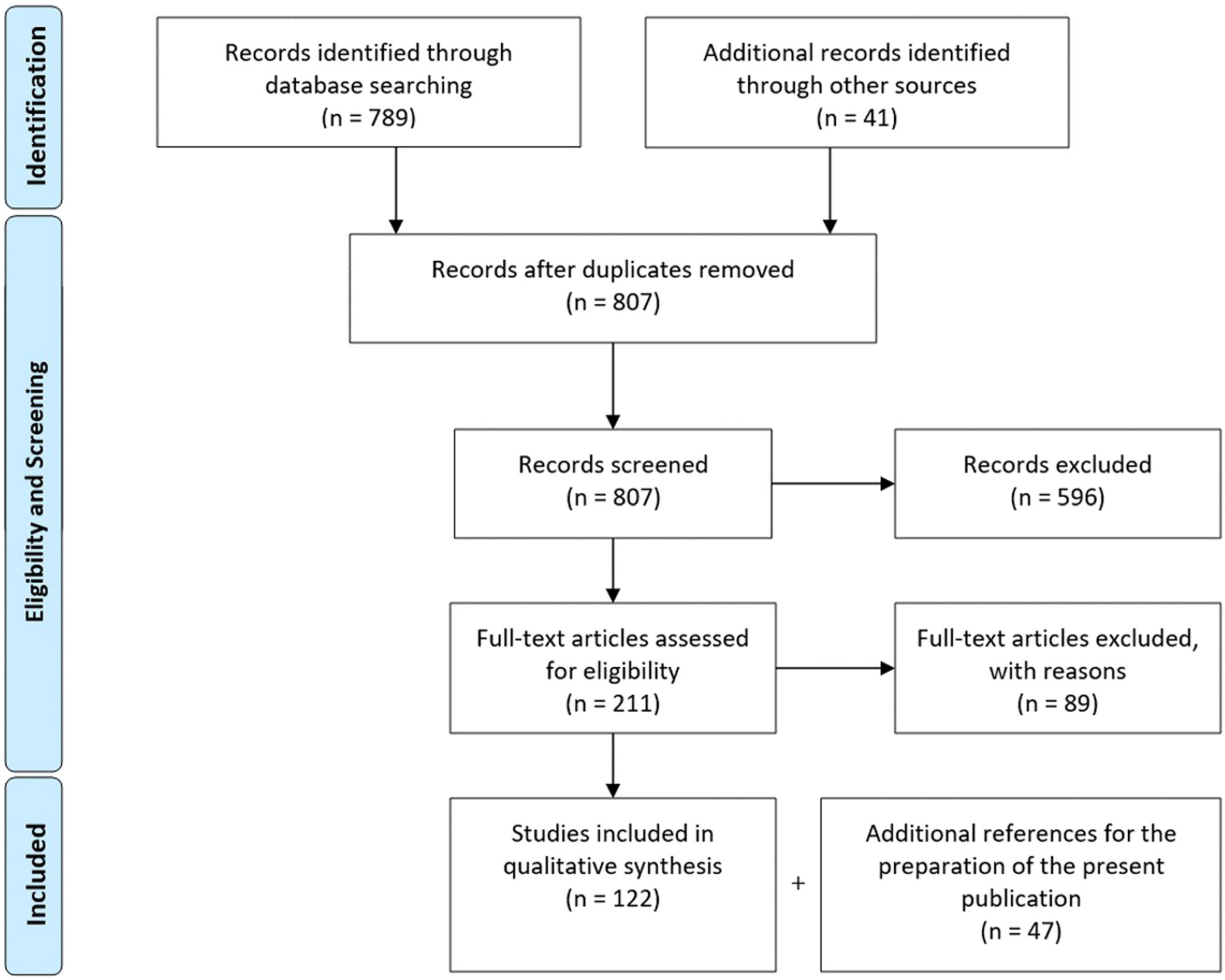

Figure 1: Modified PRISMA flow diagram.

3 Results

3.1 Origin and current status: the development of intelligent clothing from research to concrete applicability in diverse life situations

In 1999, Gopalsamy *et al.* described a shirt called the "Georgia Tech Wearable Motherboard™ (GTWM), which was designed to "monitor in a very systematic way the vital signs of humans in an unobtrusive manner." The GTWM is considered the first smart shirt worldwide. At the time of publication, the researchers focused on durability, wearability, connectivity, and functionality, such as vital sign monitoring and projectile penetration alerts for military purposes [27].

The current literature contains many highly topical developments in the field of intelligent textiles. Some products are already available on the market or are being tested on end users or patients. Many technologies are still in their infancy and require more in-depth research before being deemed suitable for everyday use. Recent years have seen a considerable increase in products and application possibilities. Smart clothing development currently focuses on power supply efficiency, washability despite technology and electronics, mechanical environment, and commercialization (Table 2).

3.2 Overview and categorization of smart wearables and smart clothing: an overview

Existing proposals for categorization and overviews of smart wearables are summarized in Figure 2. It should be emphasized that a standardized classification of smart wearables does not yet exist, but different working groups,

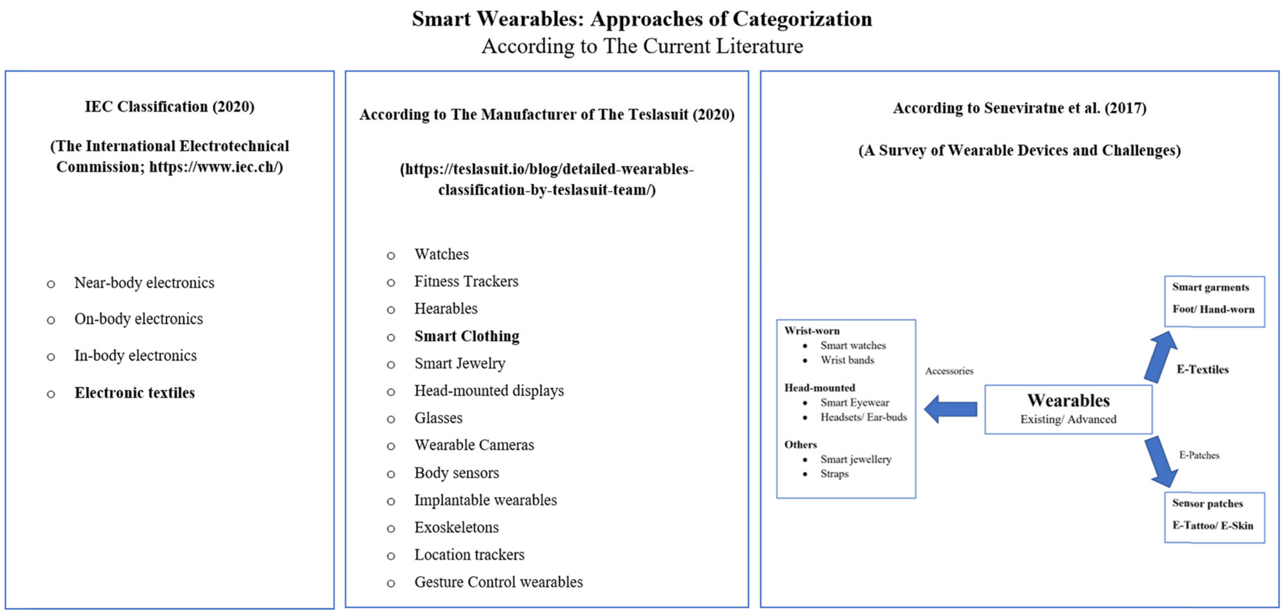

Figure 2: Examples of current approaches to categorize smart wearables.

such as the International Electrotechnical Commission (IEC), have addressed this issue [28]. The current IEC classification categorizes product types according to their localization in relation to the human body.

In contrast, Cherenack and van Pieterson described smart textiles along their historical development and identified three major categories [29]. The *first category* closely follows the vision of wearable computing. Materials with a single function were incorporated into textile materials. The *second category* encompasses various textile manufacturing methods that integrate electronic materials in a more complex way. The most recent and *third category* includes the latest developments in technologies with complex functionalities that can be implemented and integrated at the fiber level. These functionalities include measuring functions of heart rate (HR), pressure, biochemical and optical sensors, and gas-sensitive nanofibers (*e.g.*, for air-conditioning systems) that are connected to input and output devices.

Teslasuit®, a smart wearable company based in London in the United Kingdom [30], lists various products in more detail but does not form superordinate or subordinate groups. Seneviratne *et al.* developed a multilayered structure with three subgroups (accessories, e-textiles, and e-patches), each of which is differentiated into further product types [31].

In most classification proposals, smart clothes are assigned as a subgroup of smart wearables (Figure 2). Smart clothes and textiles can be further subdivided into the existing categorizations shown and described in Figure 3. Stoppa and Chiolerio presented a classification based on the functionality of smart textiles: *passive smart textiles* only have a sensory function, whereas *active smart textiles* provide reactive sensing to stimuli. The latest generation, named *very smart textiles*, can sense, react, and adapt in a more complex way [32].

More recently, Postolache *et al.* listed various smart garments according to their medical functions and data acquisition capabilities. The classification is based on collectable data such as electrocardiogram (ECG), oxygen saturation, skin temperature, and functions with respect to outgoing data and incoming data or a combination of both [33] (Figure 3).

Taking into account the various currently available categorizations and definitions, we propose a categorization that provides a comprehensive line-up of smart clothing (Figure 3). Our proposal follows the Smart Wearable Categorization of the IEC (Figure 2) and adheres to the classification of electronic textiles, as shown in Figure 4. Five groups of electronic textiles are specified based on different body regions and functions of the respective products. As an example, we outlined the applicability of smart shirts as garments with a wide range of data acquisition, which can be explained by the position of the textile on the torso. Khundaqji *et al.* also recognized this benefit of anatomic positioning of upper body garments and recently published a review article on this topic [34].

3.3 Smart wearable textiles, materials, and technologies

In the past 10 years, numerous monographs [35–37] and review articles [32,38–41] dealing with the development,

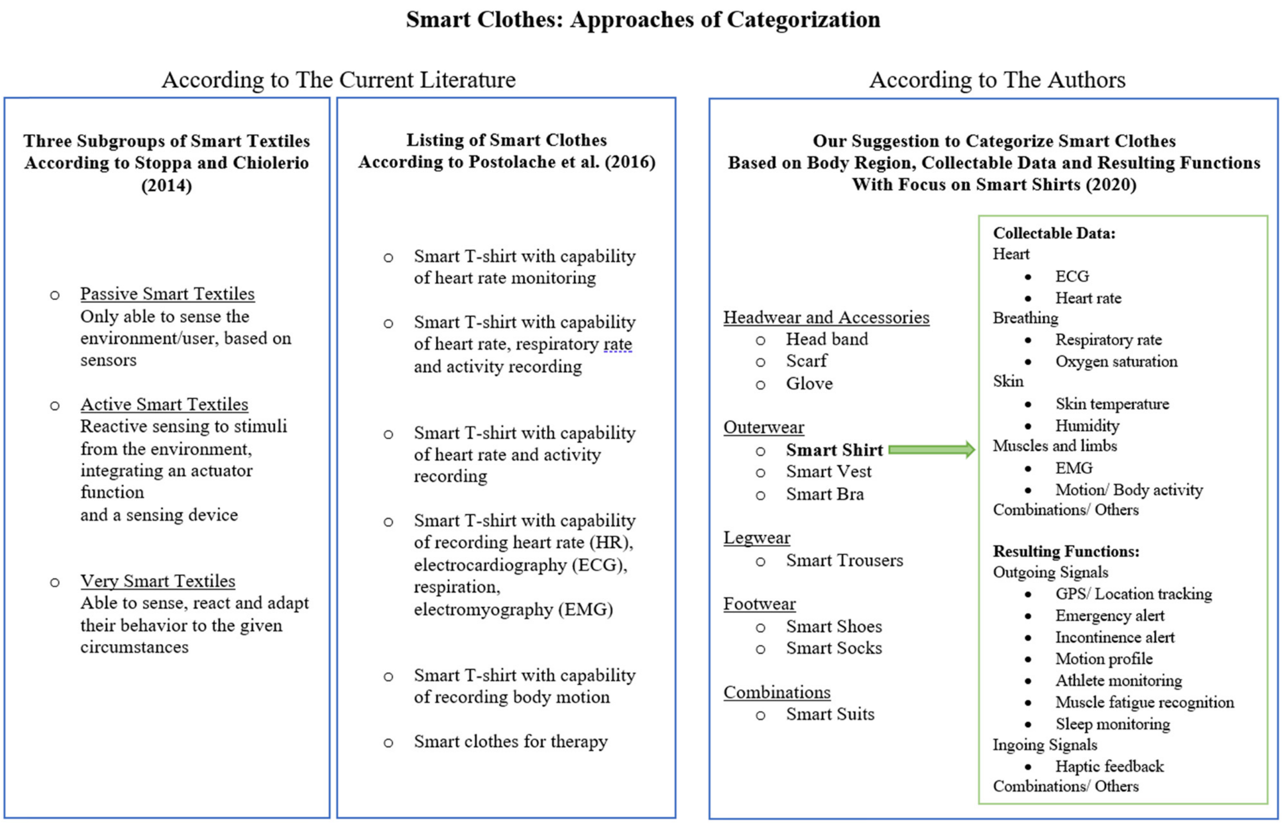

Figure 3: Current approaches to categorize smart clothes including the authors' own suggestion.

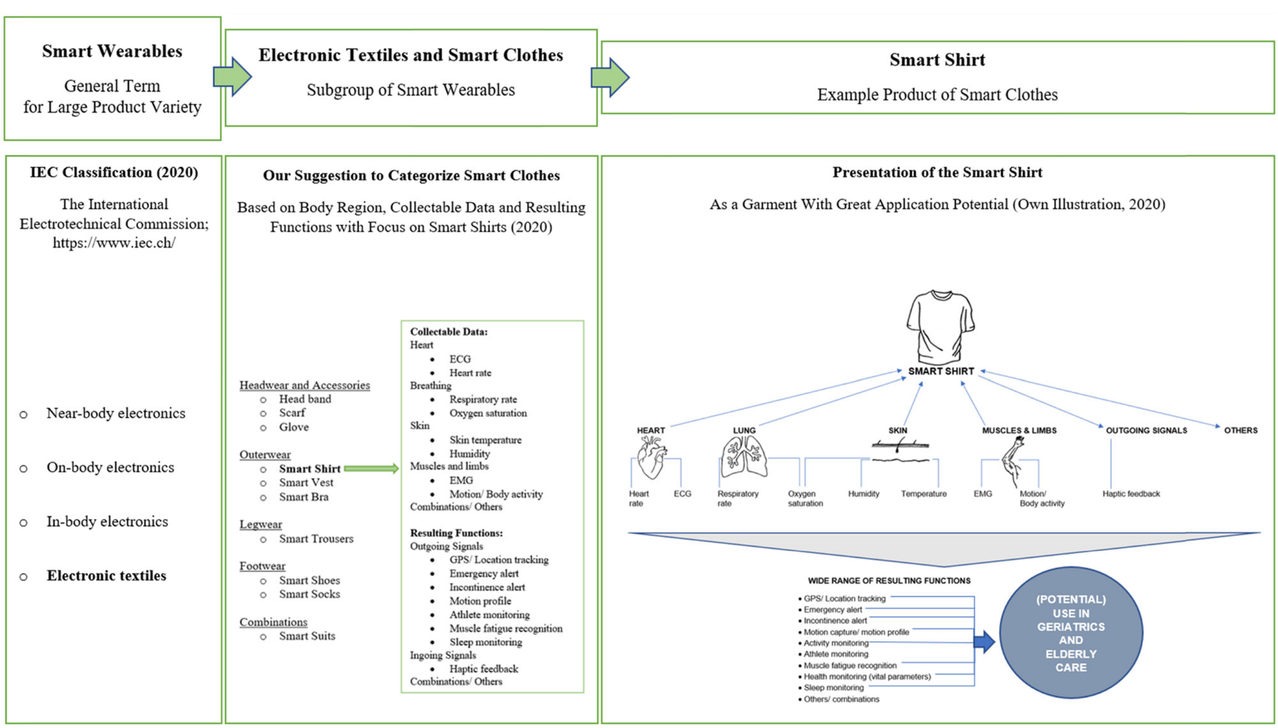

Figure 4: Positioning and categorization of smart wearables, smart clothing, and smart shirts according to the authors.

fabrication, and application of smart wearable textiles and recent developments have been published in an organized manner. In the following, we systematically summarized the development techniques and manufacturing processes from fiber to functional element. We tabulated (Table 3) the latest developments and currently used materials and methods for determining relevant health parameters such as bio-potentials, and respiratory, physical, and chemical parameters.

There are a variety of ways to produce smart clothing with different properties and functions: (1) creating textile fibers that have additional functions (*e.g.*, electrical or optical conductivity [42], sensors, or actuator properties), (2) integrating commercial off-the-shelf components such as integrated circuits or LEDs on the textile after manufacturing, (3) intrinsic or surface functionalization of fibers and fabrics, and (4) hybrid approaches that combine both commercial and textile functionalities [29]. The timing of the introduction of smart functionalities along the textile chain depends on the requirements, effort, and quality standards. Ideally, the maximum reliability of functionality, optimal mechanical properties, repeated washability, low-cost production, and high availability can be ensured.

We described the manufacturing processes along the textile production chain. At the top of the textile production chain is fiber and yarn production (Section 3.3.1), followed by two-dimensional (Section 3.3.2) and three-dimensional (Section 3.3.3) textile production, joining (Section 3.3.4), and subsequent functionalization and finishing (Section 3.3.5) [43].

3.3.1 Fiber and yarn production (1D structure)

Direct fiber production methods include dry (melt) and wet spinning, electrospinning, thermal drawing, and winding. Dry and wet spinning processes are scalable and cost-effective methods for producing fibers [44]. Electrospinning has also been used to produce fibers for textiles. In this process, a high voltage is applied to a viscous polymer liquid, resulting in the formation of a thin film containing continuous polymer fibers with diameters ranging from nanometers to micrometers [45]. Wrapping is another manufacturing process that uses soft materials to cover the surfaces of core fibers [46].

Functionalization of fibers and yarns can be achieved in the production of yarns from natural staple fibers (*e.g.*, wool, cotton) during the spinning process. For example, electrical conductivity properties are introduced into the yarn by adding a certain amount of electrically conductive staple fibers. Another method of functionalizing staple fiber yarns is winding and twisting. Electrical conductivity can also be achieved by twisting a fine metal wire around a staple fiber or multifilament fiber core yarn. While the metal wire acts as the electrical conductor, the staple fiber yarn is the load carrier. The flexibility of the whole yarn comes from the spiral shape of the wire. When the core yarn is stretched, the angle of the wire spiral becomes flatter, providing structural elongation without stressing the wire material.

In the case of synthetic continuous filaments, such as those made of polyamide (PA), polyester (PES), polypropylene, polyethylene furanoate, or piezoelectric polyvinylidene difluoride, further functionalization possibilities arise through production by melt or solution spinning (*i.e.*, compounding with inherently conductive polymers or through additives such as carbon nanotubes or carbon black particles). Special spinneret geometries can be used to produce, for example, multicomponent fibers with core–sheath or side-by-side structures [47–50]. Moreover, yarns that already contain encapsulated electronic components have also been developed. E-Thread® technology [51,52] enables the integration of electronic components into textiles, plastic parts, and composites and is based on the simple and robust microencapsulation of electronic circuits. A conductive wire in the core of a yarn along with the microscopic electronic components is virtually invisible. According to the manufacturer, this yarn can be processed like conventional yarns and remains in place throughout the life of the textile. To date, there are three areas of application for E-Thread® technology: (1) integrating LED into textiles, (2) incorporating sensors into clothing, and (3) equipping textiles with radio frequency identification (RFID) tags. In the context of this review, it is important to present possible methods of manufacturing electronic fibers/textiles for health monitoring. For example, one approach is the functionalization or conversion of conventional fibers/textiles into electronic fibers/textiles, and another is the direct fabrication of electronic fibers/textiles through fiber/textile manufacturing techniques with the addition of functional materials or structural designs [41].

3.3.2 Textile fabrics (2D production)

Textile fabrics are mainly produced by weaving, knitting, warp knitting, braiding, and nonwoven spinning [53]. The use of different filaments and yarns in the first four processes enables the structured introduction of intelligent sensor and actuator functions.

In the following, the Jacquard weaving technology [54] and the tailored fiber process (TFP) are discussed in detail. Jacquard weaving technology [55] can be used to realize complex patterns. In Jacquard technology, each warp

Table 3: Overview of parameters that can be measured, the main sensing types, examples of smart wearable textiles, materials, and technologies

Parameters and sensing types		Textile issues			Ref.
Parameters	**Sensing types**	**Smart wearable textiles**	**Materials**	**Technologies**	
Biopotentials					Angelucci *et al.* [146]
Electroencephalography (ECG)	Resistance skin-electrode impedance measurement	Intelligent headband, wearable forehead EEG, elastic bands with Velcro straps	Nylon, graphene oxide (GO), polyethylene-based foam paddings	Dip-coating of GO, drying at 80°C and reduction with HI or hydrazine	Golparvar *et al.* [147]
Electromyography (EMG)	Resistance skin-electrode impedance measurement	Textile EMG shorts, textile electrodes	PES, nylon, cotton, Kevlar Flexible foam backings Snap fasteners	Three-step dip-dry-reduce process "Hummer's method"	Ozturk and Yapici [82] Lam *et al.* [148] Svensson *et al.* [149]
Electrocardiography	Resistance skin-electrode impedance measurement	Three sewn electrodes to support 3-lead ECG data collection to compare to traditional electrodes	Nylon (preferred), PES, cotton, graphene oxide, sodium borohydride	Stitching, sewing, dip-coating, spray printing	Arquilla *et al.* [150] Ozturk *et al.* [151]
Respiratory parameters					
Pulse oximetry	Light absorption measurement, typically at 660 and 940 nm	Bracelet, earphones, headband	LEDs and photodiodes	Transmission and reflection oximetry, light is sampled at two different wavelengths and oxygen saturation is estimated from empirical equations	Aliverti [152]
Pulmonary ventilation	Inductive, piezo-electric, capacitive, piezo-resistive, and fiber optic sensors	T-shirt, strap, bra	Fiber optic sensors	A garment based on 12 fiber Bragg gratings	Massaroni *et al.* [153]
Physical parameters					
Temperature	Voltage (thermocouples), resistance, infrared sensors, change of density (liquid thermometers)	Textile-based temperature sensors embedded into wearables provide continuous remote measurements. Yarns or fibers are mostly used as sensors, *e.g.*, in "smart socks," gloves chest band, shirt, undershirt, wovens, non-wovens, knitted textiles	Cu, constantan, Cu-Ni-wires, polyaniline, PEDOT:PSS, thermoelectric inks, electrical conductive glue	Weaving, knitting, stitching dip-dyeing of cotton thread with PEDOT:PSS, integrating metallic filaments into a woven structure	Root *et al.* [154] Hudec *et al.* [155] Choudhry *et al.* [39]
Humidity	Resistive measurements, impedance measurements capacitive measurements	Cotton fabrics, bed linen, PES fabric, respirator mask	Polyaniline, PEDOT:PSS, single-wall nanotubes, polyvinyl alcohol, lithium chloride nanocomposite filaments	Printing, molecular sieve coated electroconductive yarns, spinning, using wrap spinning technology, embroidery, tailored-fiber placement, wet-spinning, solvent-exchange	Grethe *et al.* [156] He *et al.* [157] Guo *et al.* [158]
Pressure	Capacitance, resistance, piezoelectricity, triboelectricity	Shoes, insoles (wool) gloves, expandable fabric pants sensor mats	Conductive fabric electrodes, dielectric TPU	Weaving, embroidery, conductive knit fabric, dielectric layers are made of	Meyer *et al.* [159]

(Continued)

Table 3: *Continued*

Parameters and sensing types		Textile issues			Ref.
Parameters	**Sensing types**	**Smart wearable textiles**	**Materials**	**Technologies**	
		for shape, weight, gesture detection, and recognition		thermoplastic polyurethane, printing, coating, laser cutting	Pizarro *et al.* [160] Gumus *et al.* [161] Milovic *et al.* [162]
Chemical parameters					
Sweat	pH with indicator and color measurement, sweat rate with capacitive measurement	Textile fibers, both natural and synthetic (cotton, silk, PES, nylon, PDMS) waistband, net fabric (PA and elastane), elastic band on lumbar region	pH sensitive dyes (*e.g.*, bromocresol purple), tetraoctyl ammonium bromide, silicone, superabsorber, gold electrodes, polyvinylalcohol or cellulose acetate butyrate LED, photodetector PEDOT:BTB Ag/AgCl nanoparticles	Screen printing an acrylic hydrophobic paste coating with semiconducting polymer	Coyle *et al.* [163] Possanzini *et al.* [164] Yin *et al.* [165]
Glucose	Electrochemical, electromechanical, optical	Cotton fabric, microfluidic channels, wicking material, silk-fabric-derived carbon textiles	Polydimethylsiloxane (PDMS), PET, polyethylene naphtalate (PEN), polyimide (PI), parylene, pyrrole, copper sulfate pentahydrate, copper acetate, manganese acetate	Conductive threads, nanotube-modified yarn, screen printing methods, electrochemical deposition technique nonenzymatic biosensor, simple immersion method	Singh *et al.* [166] Zafar *et al.* [167]
Lactate	Capacitance, resistance, piezoelectricity, triboelectricity	Shoes, insoles (wool) gloves, expandable fabric pants sensor mats for shape, weight, gesture detection, and recognition	Conductive fabric electrodes, dielectric TPU	Weaving, embroidery, conductive knit fabric, dielectric layers are made of thermoplastic polyurethane, printing, coating, laser cutting	Shen *et al.* [168]

thread can be individually controlled by a series of harness cords. A Jacquard device is installed above the warp threads, and each warp thread can be pulled up or down individually. This technique enables the weaving of complex patterns, such as the insertion of conductive traces for heating purposes. Google has been researching smart garments for many years as part of the Jacquard project [56] and launched the first garment in collaboration with Levi's.

Embroidery is a method of applying yarn materials to a textile in a specific pattern. A more advanced version of the embroidery process is the TFP [57]. TFP technology is an engineered embroidery technique that allows fiber placement along main load paths and near-net preforms for fiber composites. The principle is derived from embroidery, in which the upper and lower threads create double stitches that then fix the reinforcing fibers to the substrate. This method introduces a third thread system that enables the precise placement of sensor threads, tubes, or stiff materials such as metal wires [43]. The obtained electronic fibers can be processed into textiles using various textile technologies. Electronic textiles can also be produced by embedding electronic devices or electronic fibers into conventional textiles by weaving, knitting, embroidery, or simply by interlacing threads of woven fabrics.

3.3.3 Three-dimensional textiles (3D structures)

3D textiles are three-dimensional structures produced by various manufacturing processes, such as weaving [58], knitting [59], braiding [60], nonwoven processes [61], or alternative technologies, such as three-dimensional printing (3DP). The latter technique enables the production of highly complex products and offers customization options for the user. This process is attracting a great deal and is promising for textile and fashion industries. Xiao and Kan [62] provide an up-to-date and comprehensive overview of 3DP technology for the textile and fashion industry based on recent research advances. They describe four 3DP methods for textile manufacturing: (1) extrusion-based 3DP systems, including fused deposition modeling, direct ink writing, and electrohydrodynamic direct writing; (2) 3D inkjet printing; (3) powder bed fusion stereolithography; and (4) selective laser sintering. They summarize three opportunities for the use of 3DP technology in textile manufacturing, including printing fibers, printing flexible structures, and printing on textiles. In addition, applications of 3DP technology in fashion design, functional apparel, and electronic textiles are presented.

3DP has offered some innovative solutions for the textile and related industries. Although the technology is still in its infancy, the number of projects that already present interesting solutions for current commercial needs shows the potential of this field [63,64]. The use of additive manufacturing processes such as 3DP enables the mechanically stable joining of textiles and electronic components, as well as the precise application of new material combinations.

Companies such as Feetz [65] and Three Over Seven [66] manufacture shoes using additive manufacturing processes. Another example is the start-up Joyfit [67], which proposed printing individualized bras, possibly with built-in biosensors, as a health or fitness tracking device. Since bras are worn close to the body, they are well suited for biosensor placement [68].

3.3.4 Joining

Reliable interconnections between electronic circuits remain a challenge in electronic textiles, in which circuits and components are embedded in clothing and other soft objects. Challenges include a lack of standards for materials and manufacturing processes, durability and washability issues, and incompatibility between textiles and electronic manufacturing processes. Joining technologies play a key role, as it is challenging to join smart textile parts in a way that is electrically reliable and durable without negatively affecting the form, fit, and function of a garment. The article by Stanley *et al.* [69] provides an overview of the main joining technologies that have been used in e-textiles to date and shows that few solutions have been developed specifically for e-textile applications. Existing solutions are mostly connectors developed for use in rigid electronics or textile closure mechanisms adapted to e-textiles.

There are different methods and tools to connect different components: thermal and ultrasonic soldering [70], welding [71], thermo-compression bonding, gluing, crimping, sewing, embroidery (conductive), hook-and-loop fasteners, zippers, snaps, spring buttons, pogo pins, magnets, alligator clips, and eyelets [69,72,73].

3.3.5 Functionalization and finishing

Dip coating, spin coating, impregnation with padder (foulard), coating with a doctor blade [74], and sputtering [75] are suitable for applying layers to both fibers and surfaces. Various functional layers in the nanometer to micrometer range can be deposited, *e.g.*, electrochromic, power-generating, and energy-storing layers [76–81]. Most smart wearables contain conductive layers composed of metals (*e.g.*, silver, copper, gold, nickel, aluminum), graphene [82], or conductive polymers (*e.g.*, polyaniline, polypyrrole, polyethylenedioxythiophene) [83,84]. In addition, commercially available fibers/textiles can be converted into conductive fibers/textiles by simple and large-scale carbonization processes such as thermal treatment or laser writing. Metal deposition involves dissolving a metallic material in a solvent or evaporating the metal in a vacuum and then depositing it on a target substrate. Metal deposition methods for manufacturing electronic textiles for health monitoring devices primarily include vacuum deposition, electrical deposition, and polymer-assisted metal deposition.

In addition, functionalized textiles can be produced by applying functional materials to conventional fabrics through ink-based processes such as dyeing, screen printing, and inkjet printing. The dyeing process is related to the interactions between the dye and the fiber, as well as the diffusion of the dye into the interior of the fiber and its adsorption onto the fibers. The screen-printing process usually requires printing screens and high viscosity inks. In addition, inkjet printing technology, which can easily produce customized patterns with sophisticated structures, has been used to make smart textiles. In dip coating, a substrate is immersed in a slurry and then pulled vertically out of the mixture. Detailed information on each method can be found in previous studies [41,83].

After functionalization, embedding electronic circuits in textiles can be performed in different ways depending on the choice of substrate to be used. Some of the methods include: (1) using conductive adhesive to bond components to a substrate, (2) soldering surface-mounted electronic components directly to metallic organza, (3) embedding thread frames of a component directly into a circuit, and (4) "stitching" components into a conductive stitched switch [38].

3.4 Smart technologies in health for an elderly population

In 2015, Khosravi and Ghapanchi analyzed 2,035 studies (published between 2000 and 2014) on assistive technologies and identified the technologies' effectiveness and application potential for older people. Eight key issues in the care of elderly individuals for which assistive technologies might be used were identified: (1) dependent living, (2) dementia, (3) risk of falls, (4) chronic disease, (5) social isolation, (6) depression, (7) poor well-being, and (8) poor medication management. The assistive technologies were categorized into six clusters: (1) robotics, (2) general ICT, (3) sensor technology, (4) telemedicine, (5) medication management applications, and (6) video games [85]. The authors were able to show that some assistive technologies are considerably effective at changing and enhancing the daily lives of elderly individuals.

Ghahremani and Latifi investigated the multidisciplinary environment for e-textiles, consisting of textiles, electrical engineering, and information science. Describing manufacturing processes, materials, system integration, and applications such as public safety, health care, fashion, space exploration, military, sports, and consumer fitness, the authors identified several possible applications of intelligent textiles. The authors propose clinical and monitoring applications for the health care sector in which textiles perform functions as actuators or sensors for communication purposes [86] beyond the typical characteristics of protection and aesthetics.

In the Netherlands, a team from the Department of Industrial Design at Eindhoven University of Technology [87] is investigating the application of smart textiles, including smart clothes, for use in services such as health care, which they termed *smart textile services*. As an example, developers presented a cardigan that can provide audio feedback that has many properties suitable for everyday use (non-stigmatizing appearance, comfort, and long-term data acquisition). Developers recommended applications in geriatric (*e.g.*, dementia) or rehabilitative (*e.g.*, physiotherapy) environments. Within the holistic approach of "smart housing," smart wearables are seen by some authors as important components of a complex network for monitoring and caring for elderly individuals [13].

3.5 Smart textiles: product examples and current studies

With the increasing interest in smart textiles, the number of scientific research papers is also growing steadily. Taking into account different focal points, an increasing number of review papers have provided the best possible overview in this research field [71,88,89].

Khoshmanesh *et al.* focused on three topics (personalized health monitoring, smart gloves and prostheses, and assistive technologies) in the field of textile smart prosthetics and described corresponding prototypes and possible applications [90].

Dulal *et al.* addressed the sustainability aspect of smart clothing, thus reconciling two major topics moving research [91].

A common focus in the worldwide development of intelligent textiles, especially smart shirts, is electrocardiograms. Some such prototypes are already collecting promising data [92–97], and some ECG shirts (such as the one from Xenoma Inc., Japan [98]) have already made the leap into applications in medical diagnostics.

A recent 2019 study reported on the applicability and validity of a smart shirt with a 12-channel ECG function. Two study groups equipped with either an ECG shirt or a standard device were compared over several periods of 3 min each. The collected data showed that the validity and applicability of the smart shirt over the short testing period were reasonable and promising [93]. A similar study using a smart shirt with 12-lead ECG equipment and a smartphone as the end device successfully tested the feasibility of all-day data collection powered by a small coin cell battery within the shirt. In addition, the researchers noted that the material composition was inexpensive and therefore potentially suitable for everyday use [99].

Furthermore, cardiac arrhythmias can be reliably detected by replacing conventional sensors of the body patch type with dry electrodes integrated into textiles while maintaining comparably reliable data acquisition with an accuracy of 98.2 ± 2% [100].

Mansoor Baig *et al.* provided various possibilities of wearable health monitoring devices with a focus on the recording of ECG data related to older adults; however, substantial drawbacks, such as data security, patient restrictions, short battery life, and a lack of consumer acceptance and medical professional feedback, must be considered for the successful use of the devices [101]. Another recent work described a smart shirt with electromyograph (EMG) measurement function to assess and display muscle fatigue, performance, and muscle activity limits. The system was able to adequately monitor EMG activity and provide valid data for sport applications but has not been evaluated for use in elderly individuals (*e.g.*, to assess frailty) [102].

Other studies [40,103] have evaluated smart clothing in subpopulations, such as elderly people in need of care or nursing. Active ageing with the aid of smart clothing is also gaining increasing attention.

Many prototypes under investigation are providing increasingly valid data. Acceptance by older populations also seems to be achieved, especially since the coming generations will be increasingly familiar with technical devices. Criticism is often leveled at the fact that currently small pilot studies are often still being carried out and there is a lack of large studies. The authors also point out aspects such as data security and striving for the most independent and proactive use of smart clothes possible.

In a literature review, Bravo and Muñoz investigated wearables (also partly non-textile) with regard to their application potential among elderly people, especially in rehabilitation, as well as in consideration of monitoring and safety [104].

Wang *et al.* examined various technologies, including smart clothes for use in the care of elderly individuals, and named three categories by which the technologies examined were classified: (1) real-time vital sign monitoring, (2) indoor positioning, and (3) activity recognition. Based on their results, the authors recommended an extension of the usual data collection of smart garments. In most cases, such data collection consists of vital sign monitoring and activity or motion capture and should be extended by the "positioning" function for geriatric purposes. The authors found this parameter to be a useful extension because of the increased risk of illness and falls at advanced ages [105]. In *Wearable Systems for Health Care Applications* published in 2004, wearable systems and related product types were presented in terms of their properties and potential applications in the health care sector. The authors classified wearables as a special form of ubiquitous computing because of their context sensitivity and classified the products according to their areas of application, including surveillance, mobile treatment, assisted living systems, and wearables for medical personnel. One focus of the work was the successful interaction between the respective system, the environment, and the patient. The authors described four characteristics that a product should fulfil for this purpose: (1) seamless integration of the system into the outfit, (2) the ability to react to context information in a meaningful way and without patient interaction, (3) the ability to generate context awareness through sensors, and (4) usability even with low cognitive abilities. If the systems investigated are successfully further developed and used, the results of the research point to a future improvement in the quality and reduction in the costs of care for the elderly population [106].

Other important aspects of successful monitoring of geriatric patients include body posture and activity. These were evaluated by Lin *et al.*, who integrated real-time posture monitoring and emergency warnings into a smart vest. Using the technology acceptance model, the applicability and adoption of this garment was tested in a group of older study participants. The results showed excellent applicability and good acceptance [107].

In the following section, we provide additional product examples of smart clothing (Table 2). Various garments and appliances were selected for their functionality, applicability, and textile properties. They are intended to provide a representative overview of the most recent developments worldwide. All products shown in the table have textile as well as technical functional properties, which serve to acquire data about the respective condition of the user. To provide an exhaustive overview, products that have not yet been specifically designed for older adults and geriatric settings but that may have potential for this group were also selected. The variety of developments ranges from socks to smart bras to full-body clothing. These are competing products in the sports and health sector with (potential) relevance for geriatric settings. *Sensoria* artificial intelligence sports include, for example, socks with distinct features, such as tracking functions for cadence, force and gait variables, which may also be useful in gerontology [108].

The shirt *Hexoskin* offers data acquisition and monitoring functions with relevance to the health sector [109–111]. The functions of the elastic material include recording capabilities for the following values and vital parameters: cardiac sensors that collect electrocardiogram (ECG) and heart rate (HR) data, respiratory rate intervals and Q-, R- and S-waves event detection, movement sensors that record steps, acceleration and energy expenditure as well as breathing sensors for breathing and respiratory rate, tidal volume (VT), inspiration and expiration events, and related quality assessment channels. Furthermore, functional sleep measurements are also included [16]. The validity of the experimental values, such as HR, breathing rate, VT, minute ventilation, and hip motion intensity, were evaluated compared to standard measurements, which resulted in nonsignificant differences between *Hexoskin* and the respective "gold standard" [112].

BWell Health Wearware female (*X10X) and male (X10Y)* shirts meet the respective requirements of the female and male physique and therefore represent two adapted products whose field of application should also correspond to that of the older population. The two different garments have strain gauges for respiration measurement, a total of ten dry electrodes for ECG acquisition and a device for data collection and transmission to a terminal (tablet, computer, or smartphone) or a secure cloud storage. The garments are already certified in Europe (CE) as class IIa medical devices and therefore can be used by physicians for data acquisition and resulting diagnoses.

Teslasuits, consisting of jackets and trousers, accommodate a body haptic feedback system *via* electrostimulation. These garments are also equipped with an integrated biometric system that measures vital parameters and records body position and movement. The in- and outgoing data can be connected *via* Bluetooth so that individual scenarios for training and virtual reality can be created. The applicable areas for athletics, enterprise, rehabilitation, and public safety with respective platform features are presented on the manufacturer's website (Table 2). Applications for older people are conceivable but have not yet been established. *Xenoma* from Japan developed a combination of shirts and trousers ("e-skin"). The garments are mainly used for real-time motion capture using measurements of the deformation along e-textile sensors [33]. The company developed a so-called printed circuit fabric, which integrates devices and sensors in circuits on the fabric. Various e-skin product types are available. These items include further and individually developable apps, baby monitoring, accident prevention shirts for motor vehicles, ankle bands for sleep improvement, and sleep and lounge pyjamas for the well-being and health monitoring of elderly individuals. Further functions specifically for the health sector and vital sign monitoring are under development. A developer kit offered by Xenoma called e-kin SDK contains sample APIs that identify the information from strain sensors, accelerometers, and gyro sensors. Fourteen strain gauges and a hub in the middle of the chest provide data acquisition and processing. The hub includes a three-axis accelerometer and three-axis gyro sensor as well as a Bluetooth interface, ensuring connectivity to multiple endpoints. This equipment should be the basis for desired developments and new areas of application.

Enflux developed motion capture clothing consisting of shirts and pants. Ten small inertial measurement unit (IMU) motion sensors (small IMUs) with a chest module form the basis of this clothing. *Enflux* clothing is already available and offers Bluetooth and connectivity for applications such as Blender and Unity. The material, a PES–Spandex blend, is machine washable, and the electronic nodes, whose functionality consists of motion capturing, are removable, making it already user friendly. *SmartsuitPro* from *Rokoko* includes 9-DoF IMUs and a hub for connectivity and connecting cables, all built into nylon-based fabric. Adjustable tightening straps are available for individual size adjustment. Connection software is based on Windows and Mac, and the applicable plugins are Unity 5, Unreal Engine or MotionBuilder. In line with this equipment, SmartsuitPro is mainly used for motion capture.

Neuronmocap from *Noitom* belongs to the same product group as smart clothing for motion capture. The company already offers very small IMUs in its suite, which make it easier for the wearer to perform natural movements with little additional weight. This product is also mainly used in the virtual reality industry and offers application possibilities for athletes and others.

The Center for Functional Fabrics at Drexel University (USA) is developing the *smart fabric belly band* and *baby band*. The former is a smart fabric belly band for use during pregnancy to monitor uterine activity and assess foetal well-being. The baby band offers simplified monitoring of the newborn child after delivery and can be used in neonatology, for example. Several research groups are already investigating the applicability of these products [113,114].

The Advanced Robotics Center (Evolution Innovation Lab) at the National University of Singapore is conducting research on soft robotics in health care, especially for rehabilitation and prevention. Here, for example, the fabric-based *Soft Robotic Assistive Glove* is being developed for use in poststroke rehabilitation [115,116]. Furthermore, the *Soft Robotic Sock* for ankle rehabilitation can move the ankles of bedridden patients in various spatial directions to support rehabilitative measures [117]. Another product developed by this lab is the *ARMAS Shoulder*. This is a 2DOF Shoulder Exosleeve for shoulder rehabilitation [118]. Research is also being conducted on a wheelchair with robotic arms that can support physically impaired individuals in their everyday lives and at least partially replace missing bodily functions (especially movements of the upper extremities) [119].

Xu *et al.* presented in an article the so-called *smart sleeve* for the detection of (everyday) human body movements. This is a sleeve made of a soft and stretchable textile pressure sensor matrix, which can be attached to common clothing and was successfully tested among 14 subjects in this research work. The corresponding dataset was made publicly available [120].

For monitoring heart rate variability (HRV) as an expression of the regulatory capacity of the autonomic nervous system, the *Ambiotex smart shirt* was investigated at the German Sport University Cologne. Here, while smart shirts were generally promising, the measurement accuracy of the smart garment studied depended substantially on the intensity of physical exercise and stress. The most accurate data were obtained at rest, while the accuracy decreased under increasing load. There is still potential for improvement with regard to this aspect [121].

An exploratory study in Denmark is currently investigating the *OncoSmartShirt* for home monitoring of patients during cancer treatment (start of patient inclusion in May 2022). The aim of the project is to explore how wearables and biometric data can be used as part of symptom or side-effect recognition in patients with cancer during treatment to potentially improve the patients' quality of life [122].

As a successful example in the preventive field, the *NEVERMIND System* (smart shirt and app) was investigated in a pragmatic, randomized controlled trial involving 425 subjects with different but severe underlying diseases with regard to the development of depressive symptoms over a period of 12 weeks and was shown to be significantly superior to the usual standard care. The subjects who had used the system developed significantly fewer depressive symptoms [123].

Another product example from the rehabilitation sector is the *Double Aid (DAid) smart shirt* investigated for subacromial pain syndrome, which detects even slight shoulder movements and provides the patient with feedback on the accuracy of the movement, enabling him to correct the movement [124].

In a clinical trial from January 2022, the *Tyme Wear smart shirt* was examined in comparison to the existing laboratory equivalent *Parvo Medics TrueOne 2400* with regard to its data validity in the collection of personalized ventilation thresholds. A certain reliability was shown here, but there was no significant advantage in data acquisition or validity [125].

Avellar *et al.* developed a photonic smart garment with 30 multiplexed polymer optical fiber sensors combined with AI algorithms, which was evaluated for its ability to classify human activities (standing, sitting, squatting, arms up and down, walking and running). Highly valid data were shown, so the authors proposed the garment for use in health care in the future [126].

Additionally, with the main function of motion capture but potential other functions, such as heart rate (HR) and ECG recording, *Bioman*$^+$ and other products were elaborated in cooperation between *King's Metal* Fiber and *AiQ Synertial*. AiQ developed Bioman$^+$ and presents application scenarios on its website, including for endurance sports such as marathons and cycling as well as ECG monitoring vests for elderly care. More product examples that have thus far been developed and used primarily for athlete monitoring but may also have potential for health monitoring applications are athlete clothes from *Vexatec*, *Athos Training System*, and *Sensoria Artificial Intelligence Sportswear* (Table 2).

It is important to emphasize that many of the smart garments under development (prototypes) are far from being suitable for use as medical devices but show great potential and are already established in private use. Approval for use in health care will include proof of high-quality standards as well as safety and performance requirements that are strictly regulated by law. To give an example, Xenoma Inc. has already received approval for its e-skin in Japan to carry out outpatient long-term ECG measurements, the recordings of which are then evaluated by medical personnel. The costs are already covered by health insurance companies.

3.6 Medical demands

For medical purposes, there are some requirements for intelligent clothing, which partly differ from previous developments and go beyond the requirements of the military, private athletes, and gaming applications. The medical applications are manifold and conceivable; for example, there are applications in obstetrics (child activity in the womb [113]), cardiology (ECG and vital parameter recording, for example, after myocardial infarction or for the detection of cardiac arrhythmias), pneumology (especially breathing signal, pulse oximetry and HR for patients with chronic obstructive pulmonary disease, asthma, sleep apnoea syndrome, and others), pediatrics (neonatology, vital parameter recording, incontinence recording and warning, and temperature measurements), neurology (motion recording, incontinence recording,

recording of vital parameters, and EEG, for example, in post-stroke rehabilitation [127]), sleep medicine (breath recoding and sleep recording), rehabilitative medicine (recording of movements and vital parameters), and geriatric medicine (holistic patient monitoring with incontinence recording, recording of temperature and vital parameters, falls, sleep, and GPS tracking, for example, for patients living alone or suffering from dementia). For the latter, it is exceptionally important to investigate the right materials for high data validity, wearing comfort, and durability of textiles. Because of the increase in the number of elderly individuals in the population and the resulting additional burden from the care and nursing of this population, the functions already mentioned above could be an important step towards providing adequate assistance in care.

Incontinence, increased frailty, tendency to fall, cognitive loss including dementia, and sleep disorders are among the most common complaints with advanced age. For all these concerns, intelligent clothing can be helpful, for example, by detecting incontinence, tendency to fall or pathological vital parameters and then sounding an alarm. In addition, intelligent clothing could be used to detect sleep disorders, which could save older adults, in particular, from having to undergo a complex sleep laboratory (polysomnography) examination. An important aspect that particularly affects dementia sufferers is loss of orientation. With GPS tracking, it is already possible to determine a location by wearing intelligent clothing, which would also be a conceivable field of application.

In a recent review, Tat *et al.* provide an update on smart textiles in the two broad contexts of (1) sustainability and (2) personal health care (diagnostic and therapeutic applications, review of recent studies, and listing of examples) [128]. In this and other contributions that address uses in health care, it is postulated that if applicability, sustainability, and data validity are improved and personal rights and data protection are adequately taken into account, smart clothing will be applied in future health care practices [129–132].

3.7 Technology acceptance by an elderly population

Often, older adults have difficulties learning new things and adapting to new situations. General theories for acceptance as well as approaches specific to elderly individuals have been proposed, such as the Technology Acceptance Model (TAM and TAM2) [133,134], the Elderadopt model [135], the Senior Technology Acceptance Model [2], and Dynamics In Technology Use by Seniors [136]. To understand whether and how older patients deal with these new technologies and developments, several studies have been performed. One of the largest exploratory studies, entitled "*Elderly persons' perception and acceptance of using wireless sensor networks to assist healthcare,*" examined attitudes, perceptions, and concerns about new technologies in the health care sector, using wireless sensor network technologies as an example [1]. Sixteen concepts in relation to elderly participants' perceptions, concerns, and attitudes towards wireless sensor systems were identified by means of focus groups and a literature review including an examination of known models. These concepts were divided into six themes that described the influencing factors relevant to the research question as follows: *independence*, *perceived impact on quality of life*, *concerns associated with examined technologies*, *user personal preferences*, *design preferences*, *and external factors*. In addition, the cost factors and maintaining independence with increasing age were of great value to the respondents. The authors' findings indicated a generally positive attitude of the study participants towards the investigated technologies. Furthermore, especially in the case of elderly or disabled people, the question of how an ethically adequate inclusion of people as active users of smart textiles can be implemented should be asked. There have already been several studies on this still small field of science. For example, Peine *et al.* are developing and shaping the new academic field of sociogerontechnology. Here, demographic change towards an ageing world population and technological progress are viewed as overlapping and mutually dependent coevolutionary fields [137]. Another interesting question in terms of technology acceptance is the question of any sex distinction between males and females. There have been scientific studies on this topic for many years, which have produced heterogeneous results. Basically, there are sex differences in behavior when dealing with technologies. Many (meta-)analyses also show that men still have a more positive attitude or a more positive self-perception towards technology use than women. Over the last few years, there has been a reduction in sex differences in the dimensions of affect and self-efficacy, but women still seem to have less conviction about their abilities to use technology. However, according to the studies, there is hardly any difference between the two sexes in terms of goal achievement [138,139].

To complete the content of this work, a rough critical examination of social science issues in the context of smart textiles was also developed. Smart textiles and garments seem to contribute to more comfortable hospital treatments and medical care by making the patient environment more comfortable. This could be a positive contribution to future patient care. Examples of this are the abovementioned baby band and belly band products in the field of obstetrics and neonatology [113].

4 Discussion

Demographic changes and the resulting challenges of caring for an increasing population of elderly individuals could be addressed by using new technologies, including smart clothing. However, the available information summarized in this review allows only a preliminary assessment of the usability of smart clothes for meeting the needs of an ageing population: older people must be considered separately in the context of new technological developments; on the one hand, they suffer from age-related physical and mental ailments that can make it difficult to dress, handle, and wear such smart shirts and textiles.

The presented products, which are in different stages of development, some of which are already available, cover many diverse application areas. The validity of the measurement methods using textile sensors is increasing and is fairly reliable overall and progressively meets the steep standards for medical devices.

Moreover, a very important aspect to be considered is acceptance and practicability among elderly individuals. As this is a distinct population group with special requirements and needs, some studies have been performed that addressed these aspects; from the findings, older people generally perceive these new aids as helpful and assess them positively.

Pioneers in product development, such as Hexoskin, Teslasuit, BWell Wear, and Xenoma, who represent smart shirts and trousers, carry considerable potential for the health care sector. The aim here is not only to bring paying customers and institutions closer but also to implement corresponding application possibilities in geriatric care. The basic data to be collected in the two sectors (private users *versus* the health sector) differ only marginally from each other, apart from the fact that the latter has higher demands for evidence, validity, and other standards in medical applications. As shown above, initial studies are already pointing to the validity and reliability of smart clothes, so the first steps towards approval in the medical field have been taken. For example, the products from the Italian company *L.I.F.E.* have already overcome this hurdle and are CE-certified.

This review contributes to the current research situation by providing an overview of the application areas, materials, and underlying technologies as well as existing product examples of smart textiles and clothing. This can be used for future research projects to follow up with more specific studies. In the following, some research directions are presented that could be further investigated.

The available evidence predominantly provides information regarding a positively evaluated trend towards smart clothing among older people for their health monitoring. Smart textiles and clothing previously used for other purposes need to be tested in appropriate studies among older individuals so that living conditions, restrictions, and requirements can be adequately taken into account. Such studies could be carried out in larger groups of patients both during everyday activities, such as household and leisure activities, and during night-time periods. It could also be helpful to evaluate which patient data in general geriatric use could be the most meaningful or beneficial for these patients so that as many people as possible can benefit from smart textiles and clothing in a broad range of applications. Even if the textile processing of health monitoring is assessed positively overall, the concrete use and application, skin compatibility, and wearing comfort of clothing among older patients should also continue to be investigated and strengthened. Existing care processes and systems could also be investigated with regard to the possibility of integrating smart clothing and textiles. In the context of the present work as well as for consideration in future studies, the term active ageing should be mentioned. Smart textiles and garments should be researched not only in terms of their applicability, especially in health care, but also, in terms of ethical inclusion instead of mere monitoring. Smart textiles are classified under the Internet of Things and are therefore also a potential target for attackers. However, IT security in this area has not yet been systematically researched. Scientific investigation of the field of IT security of smart textile products and the transfer of existing security concepts as well as the development of secure, innovative prototypes are therefore necessary in the interest of patient safety and part of the future research and development of smart textiles for the health care sector, not only in the gerontological field.

5 Conclusion

This review provides an overview of the latest studies on and developments in smart clothing with a focus on usability and acceptance for an elderly population.

Smart textiles and clothing have great potential for future use in the elderly population according to evidence from current studies and existing products. However, the respective products must also be developed and enhanced with regard to wearing comfort, user friendliness, acceptance, and targeted data acquisition to meet the special needs of older people. Issues concerning data safety and data use (*e.g.*, data access authorization) and ethics (*e.g.*, confinement of personal freedom) must be addressed for use in medical care, especially in an elderly population. In the near future, however, we see great application potential in geriatrics and in the care of elderly individuals.

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