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Review

A Review on Wearable Product Design and Applications

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Abstract: In recent years, the rapid advancement of technology has caused an increase in the development of wearable products. These are portable devices that can be worn by people. The main goal of these products is to improve the quality of life as they focus on the safety, assistance and entertainment of their users. The introduction of many new technologies has allowed these products to evolve into many different fields with multiple uses. The way in which the design of wearable products/devices is approached requires the study and recording of multiple factors so that the final device is functional and efficient for its user. The current research presents an in-depth overview of research studies dealing with the development, design and manufacturing of wearable products/devices and applications/systems in general. More specifically, in this review, a comprehensive classification of wearable products/devices in various sectors and applications was carried out, resulting in the creation of eight different categories. A total of 161 studies from the last 13 years were analyzed and commented on. The findings of this review show that the use of new technologies such as 3D scanning and 3D printing are essential tools for the development of wearable products. In addition, many studies observed the use of various sensors through which multiple signals and data could be recorded. Finally, through the eight categories that the research studies were divided into, two main conclusions emerged. The first conclusion is that 3D printing is a method that was used the most in research. The second conclusion is that most research directions concern the safety of users by using sensors and recording anthropometric dimensions.

Keywords: wearable product design; wearable technology; 3d printing; smart devices; health; sensor technology

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1. Introduction

Wearable technologies nowadays are incorporated within products and define a fast-growing category of product design. Demands of modern life, combined with the needs of people, aided by new manufacturing methods have led to more frequent use of wearable devices. This type of product has a common feature which is related to its placement on the human body and its direct interaction with the user. A differentiation that exists between these products is the method of their placement on the human body as this can be carried out in a numsber of ways. For example, there are products that are worn on the human body like a simple garment, while others are attached to the human skin with special adhesives. In many cases, a wearable product can even fit into a user's clothing. The definition of the placement method is set by the method and the reason of using the respective product/device. A wearable product/device follows the user in any activity and offers a series of advantages over the corresponding traditional ones. These products or devices can record health data (such as heart rate) throughout the day and offer an improved overall picture of the users' health compared to a laboratory measurement that would otherwise be performed occasionally at request on site [1]. In the field of health, several devices are designed in order to assist the user and his body [2,3]. Another important feature of wearable devices is the direct interaction with the user. This can be realized either by communicating with the device itself (e.g., user interface, etc.) or through the use of a computer-based system [4]. Computational design also offers additional opportunities in product development. The current paper presents a review of wearable product categories that emerged through a survey of the relevant literature. Furthermore, through the proposed categories of wearable products, a classification of the products is obtained based on their characteristics, functions and applications. More specifically, this in-depth literature survey process led to defining eight main categories in the area of wearable product design (Table 1). The main categories are: three-dimensional (3D) printing technologies, applications based on anthropometric data, computational design technologies, human body kinematics-based applications, footwear, health and safety implementations, smart textiles and athletics (sports). Moreover, each category is separated, where necessary, into more than one subcategory and in every case the technologies used are presented. Finally, the review underlines a great number of applications from the point of view of each category.

The complete amount of the reviewed papers is separated into the aforementioned categories. Figure 1 provides some statistics about the individual studies and respective categories.

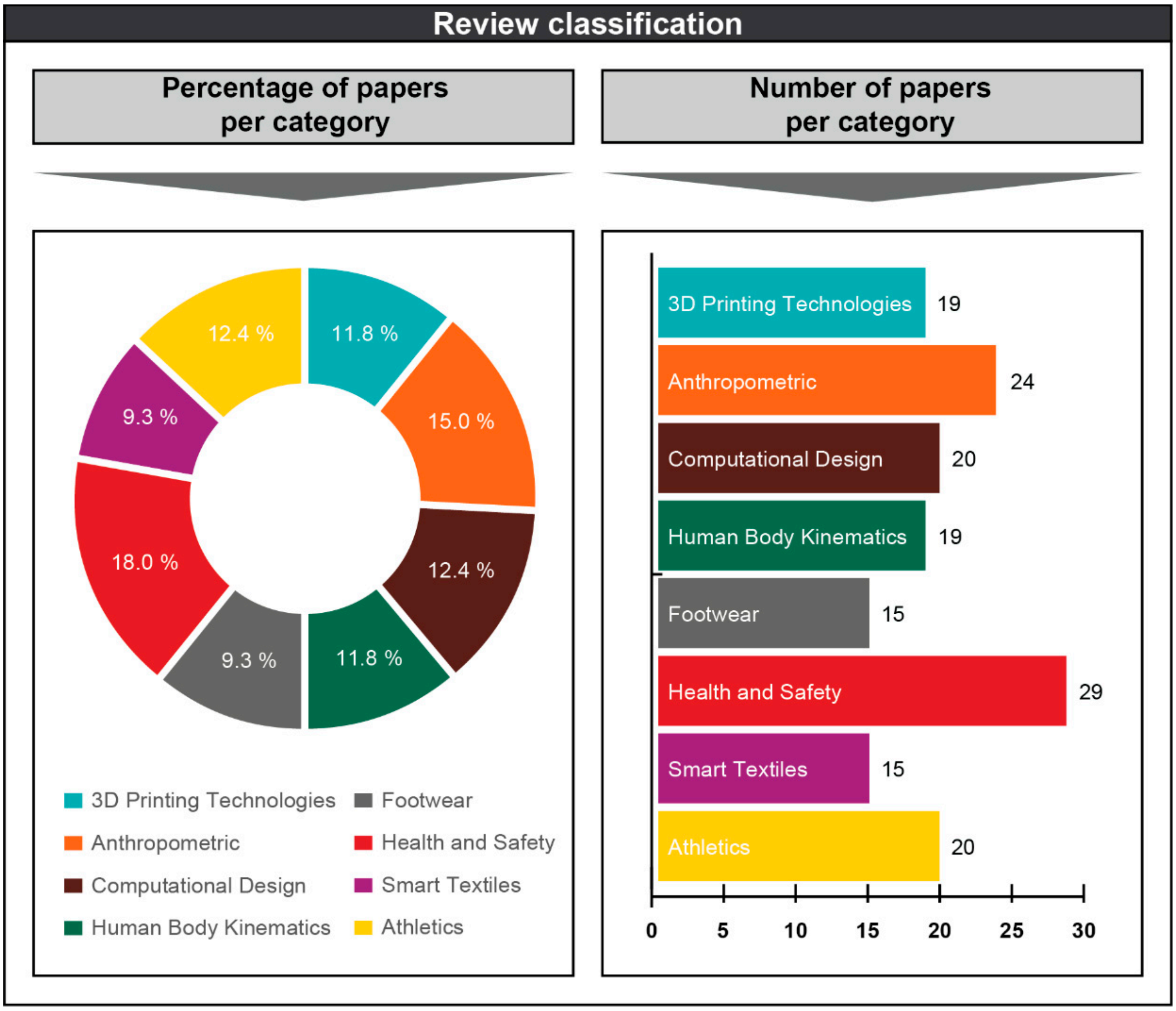

Figure 1. Review research classification.

Table 1. Summary of the wearable product design research categories.

Category	*Subcategory*	*Capabilities*	*Applications*
3D Printing Technologies	Aesthetics	- Fabric - Flexible - Comfortable	- 3D printing clothes - 3D printing accessories
	Technology	- Sensor - Data recording - Full touch	- Health check - Signal measurement
Anthropometric	Prototyping	- 3D scanning - 3D printing - Dimensional measurement	- Custom products - Unisize products
	Measurement	- Measurement sensor - Dimensional measurement - Collection of measurements	- Products for total people
Computational Design	Design Advancements	- 3D scanning - Parametric design - Automatization	- Parametric methodology of product
	Health-Based Applications	- 3D scanning - Parametric of medical design - Lattice geometry	- Design automation of product
Human Body Kinematics	Human Body Kinematics	- Anthropometric features - Measurement of joint motion - Active movements - Passive movements	- Full and half body exoskeleton - Hand exoskeleton
Footwear	Footwear	- Pressure sensor - Collection of measurements - Piezoelectric - Robot control	- Health check - Energy production - Injury recovery
Health and Safety	Equipment Design	- Medical product design - Health and stress monitoring - Health protection	- Safety at work - Fireman - Blood pressure and SPO2 monitoring
	Social Care Technology	- New sensors - System sensors - Data recording	- Heart rate measurements - Biometric and medical monitoring - Glucose monitoring
Smart Textiles	Textile Sensor	- Flexible properties - Textile sensors - Humidity sensors	- Signal monitoring - Electrophysiological measurements
	Applications	- Device control - System monitoring - Fabric	- Control by movements
Athletics	Athletics	- Biofeedback - Gyroscope and accelerometer - Motion capture	- Biometric and medical monitoring - Performance improvement

In general, to conduct the review, the steps proposed by Templier and Paré were used [5]. A sufficient number of papers were collected and categorized. Although researchers from different backgrounds develop new technologies and applications, the main target from the point of view of the authors of the current paper is to include the product design aspect within the wearable technologies developed and contribute towards the next step of designing industrial ready-to-sell products. Having that in mind, the technologies developed by the researchers should aim towards capitalizing the developed expertise in each case and design several devices that could be offered as final products to the users. Moreover, most of the studies used were published within the last five years. The main reason for this is the emphasis on the rapid development of low cost and small size technological advancement that led to the creation of more wearable products ideas over this period. The need to transfer these research concepts towards leading products in the market place is evident, together with the opportunities to further develop these ideas. The road towards the industrialization of so many ideas is widely open for producing wearables with low fabrication cost and securing significant funding for further product research and development. The number of categories selected is mainly supported by the increased number of customer-centered devices developed over the last few years and the low-cost technological advancements in additive manufacturing (3D printing technologies), reverse engineering (3D scanning technologies) and Computer Aided Design (CAD)-based technologies for product design engineering (computational product design). It is an additional argument that there is a need for a review paper in this research area with an aim to explore the trends revealed. The additional information presented in Figure 2 concerns the publication time distribution of the selected papers.

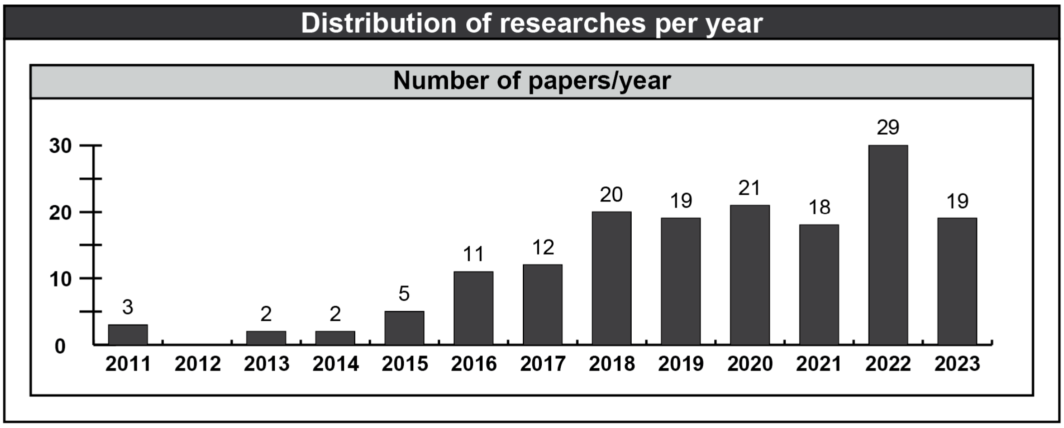

Figure 2. The distribution of research papers per corresponding year.

2. State of the Art

The present research review was carried out focused on the design and manufacturing of wearable products. In this context, the studies were grouped into eight main pillars (3D Printing Technologies, Anthropometric, Computational Design, Human Body Kinematics, Footwear, Health and Safety, Smart Textiles and Athletics). In each of the pillars, a classification was made according to the characteristics of each study. In fact, in five of the eight pillars, subcategories were created in order to better organize the review. More specifically, subcategories within the category "3D Printing Technologies" resulted in "Aesthetics" and "Technology", those in "Anthropometrics" resulted in "Prototyping" and "Measurement", those in "Computational Design" resulted in "Design Advancements" and "Health-Based Applications", those in "Health and Safety", "Social Care Technology" and "Equipment Design", and in "Smart Textiles", "Textile Sensor" and "Applications" emerged. Table 2 depicts the categories, subcategories and the number of studies used in this review.

Table 2. Names, acronyms and number of categorized research papers.

Category	*Acronym*	*Papers*	*Subcategory*	*Papers*
3D Printing Technologies	(3D P)	19	Aesthetics	8
			Technology	11
Anthropometrics	(Anthro)	24	Prototyping	14
			Measurement	10
Computational Design	(Co De)	20	Design Advancements	13
			Health-Based Applications	7
Human Body Kinematics	(Kine)	19	Human Body Kinematics	19
Footwear	(Foot)	15	Footwear	15
Health and Safety	(Health)	29	Equipment Design	11
			Social Care Technology	18
SmartTextiles	(Smart)	15	Textile Sensor	7
			Applications	8
Athletics	(Athle)	20	Athletics	20

2.1. Three-Dimensional (3D) Printing Technologies

Three-dimensional (3D) printing technology seems to be one of the leading directions for wearable design and manufacturing. A great deal of efforts are made towards capitalizing the existing additive manufacturing technologies and investing in new ones. The proposed category of 3D printing can be split into two specific subcategories with the aim to stress the main applications targeted. The Aesthetics (first subcategory) section emphasizes the appearance and convenience in using the products, while the Technology (second subcategory) side deals with the developed devices and manufacturing techniques.

2.1.1. Aesthetics

The most common wearable products for users are clothes. A series of studies are presented with aims in making clothes with 3D printing technology. This manufacturing option has been used for a number of years but lately 3D printing for clothing has increased in popularity as a method for fabrication. From an aesthetic point of view, these products combine both design and fabrication during their creation. The techniques and methodologies presented below retain many common characteristics in order to create, in each case, the final garment.

Yap and Yeong [6] analyzed and commented on the construction of a garment entirely from a 3D printer. The study carried out an analysis of all the basic steps as well as the alternative options for creating a garment. More specifically, the study was divided into two parts. In the first, the steps of the design process were described. Some of these pertain to measuring the dimensions of the human body and digitally drawing the original form. In the second part, the study focuses on the manufacturing process. At this point, the steps of the process that must be followed in order to create the garment are defined. At the same time, reference is made to various types of printers as well as to some available fabrication materials. In the end, the study concludes that in the coming years, technologies like 3D printing will be introduced in the clothing industries, adding new possibilities to them.

Pei et al. [7] carried out 3D printing of polymers on various fabrics. In this research, a set of experiments was performed comparing three types of plastic (PLA: Polylactic acid, Nylon and ABS: Acrylonitrile Butadiene Styrene) material which were used for printing on eight different types of fabrics. With several tests of prints, the full factorial set was evaluated and resulted in selecting PLA for its best performance.

Cui et al. [8] applied an online survey to a set of consumers about the creation of a garment with the use of a 3D printer. As part of the research, a prototype garment was made, which consisted of a set of different plastic material and fabrics. The collected data were then translated into individual variables, against which the new garment was evaluated. Some of the factors were Satisfaction, Purchase Intention, Innovation, Beauty, Youthfulness, Uniqueness and Appropriateness. At the end of this research, the aesthetic, expressive and functional perceptions of the consumers were evaluated.

Yu and Kim [9] used 3D scanning and 3D printing to develop dress forms in various body positions. In this study, the aim was to digitize the human body in standing and sitting positions with high accuracy. It was a tool through which dress design in apparel industries could be improved. The study began by defining the target group which in this case was middle-aged Korean women. From a set of several women, one was selected. The one that was closest to the mean of anthropometric dimensions according to an analysis of size data. A 3D scan of the selected body was then performed in a standing and sitting position. Then, dress forms were designed based on the 3D scan through 3D CAD software. At the end of the study, prototypes of both the bodies and the dress forms were made for inspection and correction.

Lee and Koo [10] combined traditional Korean symbols with modern clothing fashion. A market survey was conducted in order to find the preferences of potential Korean tourists. The outcome was to sort out 10 symbols from the "shipjangsaeng" motifs (longevity symbols). Beyond the selection of the 10 most preferred symbols from the survey, it emerged that buyers would like to see the use of new technologies such as 3D printing. Based on the selected symbols, various pattern variations were created, which could be adapted in two selected types of clothing (a short-sleeved T-shirt and a woman's dress). For the selection of materials, bending tests with two materials (PLA and TPU—thermoplastic polyurethane) were performed and the ideal printer settings as well as the maximum bending angles were defined. Valtas and Sun [11] investigated the integration of 3D printing technology within the clothing industry. The calculation of cost and manufacturing time of each garment were included. A prototype garment was fabricated with parts made of 3D printable plastics. At the end, an evaluation was carried out regarding the design principles used for the garment with an aim to use 3D printing technology for both assembly and ease of use. Jeong et al. [12] developed garments using computational design and manufacturing with advanced 3D printing technologies. The goal was to present a simple methodology for the extension of fashion products that encompassed complex geometry. Three-dimensional (3D) printing came at the end of the proposed methodology, in order to fabricate the actual prototype of the garment. The design process of two parametric patterns was analytically presented. The two patterns delivered via computational design were able to adapt to various product applications. More specifically, three additional clothes and two accessories were 3D printed. At the end, more pieces of information were presented about the problems and limitations encountered in the process. Future studies were proposed for further explorations in the area.

Wang et al. [13] presented a new method of constructing geometries using a 3D printing pen. More comparatively, it facilitates 4D printing of geometries which can provide multiple applications in everyday life. In the study, 2D path-shaped geometries printed on a flat surface were created, using the 3D printing pen. Different filling directions of the material were applied to each geometry. Next, all the 2D geometries were placed in water with temperature of 75 °C. The material used in the study was PLA, as a result the geometries were curved due to the temperature. The different printing directions caused different deformations in each geometry. The study presented all cases of routes as well as their results. In the end, various applications such as creating handicrafts and designing clothes and accessories were carried out.

2.1.2. Technology

From the point of view of technology, various researchers analyze the use of 3D printing in a more technical context. The specific tool of 3D printing could be extensively used for the fabrication of device carriers and wearable products themselves.

Padash and Carrara [14] performed a collection and analysis of human sweat using a wearable device. The main challenge of this study was the construction of a wearable device using a 3D printer. The purpose of the printed geometry was to transfer sweat through a specific passage from the skin to an electromagnetic sensor. The comparing sensor was placed inside the printed geometry. At the end of the study, a prototype construction was carried out using an MJM (Multi-Jet Modeling) 3D printer. The material used was a flexible plastic so that it fitted evenly on the skin. The device was then tested under normal conditions on the skin. Through various measurements of the test device, the correct operation of the system was verified.

Abdollahi et al. [15] developed a wearable device that was able to collect information, such as the heart rate as well as the measuring the proportion of oxygenated haemoglobin in the blood of each user. Its manufacturing process was realized with a 3D printer by utilizing the FRE (Freeform Reversible Embedding) method. The device material used was polydimethylsiloxane (PDMS) elastomer. The prototype of the construction was worn on a finger as well as on a toe, and the appropriate measurements were taken in comparison with the real ones. Measurements were displayed in real time using a tablet, while the user was at rest, sitting and walking. Yin et al. [16] built a touch and pressure sensor using a Digital Light Processing (DLP) 3D printer. The recording of touch and pressure was not performed by the electrons control but using charged ions. A combination of two materials, Polyacrylamide (PAAm)—Polyethylene Glycol Diacrylate (PEGDA) hydrogel, was chosen as the printing fluid. During the research, various prototype sensors were developed which could record several human signals, such as heartbeats, vocal cords and others. Wu et al. [17] presented the results of 3D printing with a hydrogel showcase for changing the properties of the final print. The main purpose was to create new flexible sensors that could be worn by people. In this study, a methodology for the rapid fabrication of customized hydrogels was presented. The presence of metal ions as well as water allow the electrical conductivity of the hydrogel. Based on this characteristic, deformations in the hydrogel network could increase and decrease the resistance of the electric current. In other words, every movement of the hydrogel could be precisely recorded based on the resistance. The printing method used was Liquid Crystal Display (LCD) printing, which used ultraviolet (UV) rays to stabilize the liquid resin. The final sensors printed were able to individually record the movements of the fingers of a human hand.

Loh et al. [18] delivered a metamaterial while using a 3D printer to build a capacitive sensor. The sensor was able to detect forces and movements on curved surfaces that deform. Based on its geometry and its properties, the device could be adapted to various parts of the human body. The geometry of the device consisted of a 6×6 grid on which 36 simultaneous measurements were performed. The mesh manufacturing process was divided into five basic levels using two different materials. The first printing material was Thermoplastic Polyurethane (TPU) and the second material was Electrical Thermoplastic Polyurethane (PI-ETPU) which would be used as an electrically conductive electrode. In the construction of the device's layers, PI-ETPU was used twice (second and fourth layers) and TPU three times (first, third and fifth layers). In essence, the role of TPU was to keep the two planes of the electrodes at a distance, which were met in vertical directions. The device was printed using a 3D printer on which the experimental measurements were also performed. During the testing stage, the device was fitted on the elbow of a volunteer.

Qin et al. [19] presented a flexible touch sensor using a 3D printer with the E-jet method. Silver Nanoink was chosen as the printing material because of its conductivity, the flexibility of its structure and its ability to be printed. In this study, a capacitive touch sensor was designed and printed. This proposal used two electrodes whose design allows them to be inside each other but without touching each other. Any contact of human skin could create a ground between the electrodes. Using an Arduino-based system, the hand touches on the sensor were recorded. In this paper, several tests were performed on a real prototype sensor to find the optimal shape and minimize false readings. More specifically, the lengths and thicknesses of the electrodes, as well as the distances between them, varied.

Li et al. [20] developed a new Triboelectric Nanogenerator (TENG) using a 3D printer which was 2.5-times more improved in durability than the corresponding applications made of graphene. In this study, a printing process was developed to create elastic sensors and energy generators. Various original devices were created with this method. The first device was related to the creation of a zone that would be able to charge devices with low energy consumption. The second device was related to the creation of a smart glove which would be able to control an electronic computer. More specifically, the smart glove included 21 interactive channels with which it was able to control various computer applications. The new triboelectric nanogenerator method was also tested and verified under tensile stress without losing its properties. Chen et al. [21] established a Triboelectric Nanogenerator (TENG) using a 3D printer. The key feature of TENG was its ability to conduct low-power current when forces were applied to them. In this particular study, a TENG manufacturing process was developed and entirely fabricated through a 3D printer. A key advantage of this method over traditional TENGs was the fabrication of the device without additional assembly steps. In the context of the study, two devices with integrated TENG technology were realized. More specifically, a sole was manufactured that could conduct an electric current while walking and a finger tracking system that was worn around each finger.

Qian et al. [22] developed a new liquid for 3D printing named Polyvinyl Formate (PVFm). It had the ability to solidify when in contact with water. The conductivity of the new printing material enabled the creation of flexible sensor carriers. As part of the research, two types of sensors were created. The first type applied degenerative forces to the sensor, while the second type applied compressive forces. The data was recorded through the resistance caused by the printed sensor. In the case of compression, the resistance was decreased due to the shorter paths involved, while in the case of expansion the resistance was increased due to the longer paths.

Li et al. [23] used 3D printing to create a wearable device with healthcare and motion detection capabilities. The 3D printed device consisted of a fiber gel that incorporated Poly(Vinylidene Fluoride) (PVDF) inside. The main characteristics of the device were its very high elasticity and high conductivity. Another key feature was the detection of physiological signals such as body movements. Also, the device had the ability to be self-powered, which allowed to both collect and send various data. More specifically, the device could send the data using a Bluetooth module. The study concludes that this device could find various applications in the future as a vector portable sensor based on its portability and self-powering ability.

De Tommasi et al. [24] fabricated a wearable device using a 3D printer as an auxiliary tool for a doctor. The main goal was the ability of the device to help a doctor perform an epidural operation. This specific operation required a high degree of skill from the doctor as the detection of the operation site needed great precision. Also, the small size of the epidural space increased the chances of success. In recent years, various technologies have been developed to solve this problem, but many of them could contaminate the sterile field. The device developed in this particular study was placed in the area of the thumb and its shape resembled a shell. At the bottom of the device, there were two retaining holes. To avoid various contaminations, the printed device was placed inside the doctor's glove. At the end of the research, the device was successfully tested in a real clinical scenario proving its correct operation. Table 3 schematically depicts pieces of information about the 3D printing-related papers used in this paragraph.

Table 3. Definition of the research in the category 3D printing (3D P).

3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle
Aesthetics				Technology			
Researchers		Keyword		Researchers		Keyword	
Yap and Yeong, 2014 [6]		3D/4D printing		Padash and Carrara, 2020 [14]		Auxiliary tool	
Pei et al., 2015 [7]		3D/4D printing		Abdollahi et al., 2020 [15]		Sensor	
Cui et al., 2022 [8]		3D/4D printing		Yin et al., 2019 [16]		Sensor	
Yu and Kim, 2023 [9]		Measurement optimization		Wu et al., 2021 [17]		Sensor	
Lee and Koo, 2022 [10]		3D pattern		Loh et al., 2021 [18]		Metamaterial	
Valtas and Sun, 2016 [11]		3D/4D printing		Qin et al., 2017 [19]		Sensor	
Jeong et al., 2021 [12]		Parametric design		Li et al., 2022 [20]		Triboelectric	
Wang et al., 2023 [13]		3D/4D printing		Chen et al., 2018 [21]		Triboelectric	
				Qian et al., 2022 [22]		Sensor	
				Li et al., 2023 [23]		Sensor	
				De Tommasi et al., 2023 [24]		Auxiliary tool	

2.2. Anthropometric

Both prototyping and virtual prototyping via users' body measurements led towards improved time to market and increased the customer satisfaction. Customized wearable products could be greatly affected by these research categories, while at the same time the user could feel that these wearable products were fabricated especially for him/her.

2.2.1. Prototyping

Various prototyping methods were used to materialize a set of applications on wearable products. Prototyping was undoubtably a method to produce wearable products and test its functionality and performance. It was one of the areas that was further developed together with the industrial design engineering.

Bamani et al. [25] designed a wearable device for the user's hand, which was able to record data when identifying various objects by geometry. The device used Force Myography (FMG) sensors and was able to read muscle disorders in two areas of the hand. The recording of the data was transferred to a piece of software developed for differentiating them according to the shared information. As a result, the presented device, after a period of calibration, was able to distinguish the type of the object that was held in the hand with a success rate of 95%. Delva et al. [26] investigated the degree of influence of a person's anthropometric dimensions by collecting myographic data. As part of the research, a wearable device was created, which could record the movements of the hand muscles. The aim of the study was in the first phase to collect the data from various volunteers and in the second phase to process and search for correlation of the data. The basic criterion of data processing was the anthropometric dimensions of each volunteer. Using the device, 21 volunteers performed a set of hand movements, resulting in the collection of data and their comparison. The results showed that the anthropometric characteristics of a person could affect the quality of the sensor signal by 23 to 30%, while this percentage could reach 50% when performing individual gestures.

Robson and Soh [27] sought the design of a wearable device that allowed specific movements of the finger in one hand. The device consisted of an anthropometric chain, whose rotation points were identical to the corresponding rotation points of human fingers. This particular device was placed on a single finger and could follow the natural movements of the finger. Using a 3D printer, test prints were made in order to improve the design of the device. Tan et al. [28], continuing the previous work, designed and manufactured a wearable device which allowed specific movements of all fingers on a human hand. The optimization of the device was based on the ν-constrained least square optimization, with the main goals being the weight reduction combined with the size reduction. The device consisted of four serial chains one for each finger past the thumb. Each chain consisted of an eight-bar sliding mechanism. For the design and location of the pivot points, a visual recording of a hand with various points marked on it was carried out.

Lee et al. [29] presented a wearable necklace-type device using an ergonomic design. The purpose of the research was to find the main variables that determine how comfortable and natural a wearable device felt to the user. The study involved 25 people of mixed genders and aged between 20 and 30 years. Using 3D scanning technology, it was possible to digitize the appropriate part of the body so that the design of the geometry could begin and the critical dimensions of the product could be revealed. From the results of the scans, some variables were found, and as a result the product's comfort was determined. Some of those characteristics were the width, height and angle of the side points of the neck. The study concludes that a product that was worn by humans should be designed in such a way that the user did not feel local pressures in specific areas of the body.

Shin et al. [30] measured a person's body mass index using a wearable device. The device was strapped on the wrist and calculated the electrical resistance of the body using electrodes. As part of the research, measurements were made on 163 athletes. Then the measurements of the device were compared with two corresponding devices on the market for their evaluation. The results proved that the new device had a 9% better correlation coefficient and a 28% smaller standard error.

Schauss et al. [31] designed a wearable health monitoring system based on female anthropometry. The wearable device was in the form of a garment and was worn on the chest area like a bra. This special garment was using self-adhesive electrodes and was able to record heartbeats in various environments beyond medical laboratories. During the research, the interferences and the noise that were present in the recording of the measurements were also considered and checked.

Wang et al. [32] developed a wearable Fabric Strain Sensor (FSS) detection belt which was placed on the upper arm of the user. The wearable belt had the ability to monitor the muscle deformation based on the change of the arm circumference. The device consisted of three (3) parts. The first part dealt with detecting the signals in each hand movement. The second part managed the recording of the data, while the third part was related to the wireless sending of the data to a computer using Bluetooth technology.

Anuar et al. [33] fabricated a wearable structure for children suffering from cerebral palsy. This wearable device enables them to stand up as well as walk. For the design and creation of the device, the characteristics of 25 children were individually recorded, such as the height, the weight, the age as well as the differences between the size of the limbs. Based on the measurements, an initial prototype of the construction was created, which were used by all research children based on the parameterization it can accept.

Verwulgen et al. [34] built a database (feature map) for clustering and categorizing anthropometric dimensions using 3D geometries from human heads. Through the analysis of the data, three design strategies that addressed the design of products related to heads emerged. The first design strategy was the collective form, where a product was designed to appeal to the entire population with a specific dimension. The second strategy refers to product design by user groups. In this case, some sets of the population were separated. They had some common characteristics and then specialized products were designed for them. The third and final design strategy was an individual application design where the designed product was clearly aimed at a specific user. After the creation of the feature map, an idea was developed for the design of EEG headphones that would be adapted to the human head and the statistical models of the research were used.

Kim et al. [35] analyzed facial anthropometric data in order to design a wearable beauty device. In recent years, many people had been using home facial care devices based on light emitting diode (LED) technology. The main problem with these devices was the uneven pressure they exert on the face of their users. In this study, information from a 3D database of human measurements was evaluated. Based on these measurements, the design of a new device was developed, which was worn on the face as glasses.

Paterson et al. [36] carried out a comparative study between four different manufacturing methods for a hand splint. The four manufacturing methods compared were the Laser Sintering (LS), the Fused Deposition Modelling (FDM), the Stereolithography SLA and the Polyjet^{TM}. Their evaluation criteria included surface quality, accuracy, flaw analysis, use of auxiliary parts and material cost. From the results of the comparison, it was concluded that out of the four methods, FDM was the most vulnerable splint manufacturing process. One parameter that was not included in the comparison, was the medical perspective, i.e., the evaluation using clinical trials. With the future addition of this perspective, a more complete comparative study would be carried out when constructing a hand splint.

Liu and Huang [37] described the relationship between artificial intelligence technology and wearable product design. Initially, reference was made to various features and functions of this type of product within academia. Based on the way of use, these products were divided into four main categories, i.e., the products for the upper extremities, the lower extremities, the head with the surrounding area, as well as products for the rest of the body. From the perspective of functionality, three categories emerged: (a) intelligent assistance, (b) dynamic operation and (c) body movement perception. Then there was a reference to the ways in which artificial intelligence technology was introduced into these devices. A smart-assisted backpack was then successfully designed. The aim of the design was to satisfy both functional and aesthetic requirements.

Nishida et al. [38] built a system consisting of various components for the embodiment and the perception of a child from the user's point of view via the proposed system. In essence, the behavior and daily lifestyle of a child was transferred to an adult person. The goal was to understand the key issues for redesigning products that could be used by children. This system consisted of a set of components, i.e., camera, screen, hand exoskeleton. More specifically, the camera was adjusted to the abdomen area of the adult body at approximately the height from which a child observes the world. The camera image was transferred to a screen, which was placed in front of the adult's eyes. With this in place, the user could see the space from a completely different angle. The hand exoskeleton was a device that adapts to the user's fingers and had an extension inside, for housing a child-sized robotic hand. With every movement of the user, the robotic child's hand moved mechanically. With all these devices an adult can perceive life from the child point of view. From the test results it was reported, that changing the height of the viewing angle was quite difficult for the participants. Also, several people reported that they felt under pressure when people were surrounding them. Finally, all users were asked to hold various objects such as toys using the exoskeleton, resulting in several of the objects being difficult to hold.

2.2.2. Measurement

When it comes to designing customized product for people, measuring with modern 3D scanning technology offers multiple advantages due to its digital prototypes produced. A number of studies are based on already existing datasets containing anthropometric measurements and this offers additional advantages from the designer's point of view.

Lee et al. [39,40] developed a piece of software for a 3D Anthropometric Sizing Analysis System (3D-ASAS), which managed a set of 3D scanned human heads. Three-dimensional (3D)-ASAS was based on the Civilian American and European Surface Anthropometry Resource (CAESAR) database, which holds 3D data from 2299 people. In the context of this research, 30 dimensions emerged from each scan, with which different subcategories appeared. The main objective of the 3D-ASAS software was to facilitate the design of products related to the head having set a specific population target. The same research team analyzed the anthropometric dimensions of the human ear using 3D scanning and casting methods. The main purpose was to improve the design in both comfort and ergonomics of products related to the ear. For each scan, 25 specific inter-ear dimensions were isolated against which comparisons were made. The results showed that both origin and gender significantly influenced the overall dimensions of the ear. Fan et al. [41] studied the anthropometric dimensions of the human ear in the region of China. For the analysis of the samples, 18 anthropometric dimensions were measured in 700 people. The main purpose was to collect various information with an aim to propose new ways of categorizing the sizing of ear-related products. Ban and Jung [42] improved the development of wearable products that were placed in the human ear by categorizing anthropometric dimensions. In this study, a survey was carried out which was used to collect ear geometries from 310 people, using the 3D scanning method. Then, using statistical correlation analyses for each anthropometric measurement, a comparison was made in terms of the sex, the origin and the age using a one-way analysis of variance. Through the comparisons, the digital geometries were divided into some basic categories according to their dimensions. These categories were: round, rectangular, triangular and inverted triangular ears. According to this study, this particular categorization could be applied practically in the future design of products worn on the ears.

Granberry et al. [43] developed a sizing strategy for designing a garment for the lower part of a leg. The goal was to create a functional wearable garment, i.e., a garment that could carry a set of sensors. As a result, a close and perfect fit should be an essential feature of the garment. The research used data from the CAESAR database relating to the lower part of the foot of 160 people. Baseline data were sorted and evaluated according to six clustering variables to draw the final conclusions.

Kang and Kim [44] carried out research on the changes caused to the dimensions of the human body when performing specific postures. A 3D scanning system was used to collect the anthropometric dimensions. The aim of the research was to examine the size difference in 32 areas of the human body. After the completion of the information collection, the data was processed by cross-sectional analysis software of the human body which was developed for this purpose. In the results of the research, three main correlations were observed between the movements and the dimensions of the body. Specifically, it was observed that the size of the chest was affected by the movements of the hands, the size of the waist by the movements of the trunk. Moreover, the hip area showed a change in its stretches by the movements of the legs.

Luximon et al. [45] carried out research in which the dimensions of human feet were evaluated in order to find similarities among them. As part of the research, the feet of 60 people were scanned and then digitally stored. The sizing and grading data analysis together with the evaluation method used was called Principal Component Analysis (PCA) and is considered more effective than other traditional methods, used for the anthropometric characteristics of the body.

Llop-Harillo et al. [46] evaluated two different simulation methods for controlling the motion of a robotic arm. The main goal was to approximate human kinematics, so that the movements look more natural. This new method was based on the definition of a reference point on each candidate object, which was initially defined by a human. The specific point contains the local perturbations and the local orientation of each geometry. The robotic hand according to the benchmark was much more easily able to hold various objects in a fairly natural way.

Kartelli et al. [47] commented on and analyzed the design of clothes using new technologies, such as virtual reality (VR). A modern clothing design process was presented with a new design experience direction. Some of the advantages, when using VR in design, were the minimization of the design steps during the traditional process, as well as avoiding errors. In addition, the improved interaction of the designer with the garment improved the final result in a significantly shorter period. The entire design process could be automated together with fabrication tools such as 3D printing. The research presented a brief description of the design process using the Tilt Brush program as well as some possible future uses of this technology.

Rohmatin et al. [48] designed a portable study desk and evaluated it according to the RULA method. The RULA method (Rapid Upper-Limb Assessment) had the ability to assess the upper limbs of the human body, the neck and the trunk. In essence, with the

RULA method, evaluation was achieved for the ergonomics of a condition or a product, as well as the risks that could be caused by an incorrect posture. The RULA method analyzed the position of the body as well as the influence of external factors. From the results of the RULA evaluation, it was shown that the shape and dimensions of the desk helped the correct posture of its user during the study. Table 4 schematically depicts pieces of information about the Anthropometrics-related papers used in this paragraph.

Table 4. Definition of the research in the anthropometrics category (Anthro).

3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle
Prototyping				Measurement			
Researchers		Keyword		Researchers		Keyword	
Bamani et al., 2021 [25]		Sensor		Lee, et al., 2018		Body measurement	
Delva et al., 2020 [26]		Sensor		Lee, et al., 2018a,b [39,40]		Body measurement	
Robson and Soh, 2016 [27]		Auxiliary tool		Fan et al., 2019 [41]		Body measurement	
Tan et al., 2017 [28]		Auxiliary tool		Ban and Jung, 2020 [42]		Body measurement	
Lee et al., 2017 [29]		Measurement optimization		Granberry et al., 2017 [43]		Body measurement	
Shin et al., 2019 [30]		Sensor		Kang and Kim, 2023 [44]		Body measurement	
Schauss et al., 2022 [31]		Sensor		Luximon et al., 2012 [45]		Body measurement	
Wang et al., 2016 [32]		Sensor		Llop-Harillo et al., 2022 [46]		Robotic technology	
Anuar et al., 2018 [33]		Auxiliary tool		Kartelli et al., 2018 [47]		3D/4D printing	
Verwulgen et al., 2018 [34]		Measurement optimization		Rohmatin et al., 2023 [48]		Measurement optimization	
Kim et al., 2022 [35]		Measurement optimization					
Paterson et al., 2015 [36]		Auxiliary tool					
Liu and Huang, 2020 [37]		Auxiliary tool					
Nishida et al., 2015 [38]		Sensor system					

2.3. Computational Design

A number of different applications based on computational design programming tools are able to automate the design of wearable products. Some of the applications perform without the need of the designer and in some other cases, a limited amount of intervention is required. The designed wearable products are mainly customized to the user's 3D geometrical characteristics.

2.3.1. Design Advancements

Urquhart et al. [49] analyzed the term 'computational design' and its contemporary connection to human-centered product design. They recorded various terminologies related to each other, i.e., computational design, parametric design, design optimization and generative design. The aim of the research was to analyze how to connect the new design methods in a more human-centered context.

Lazaro Vasquez [50] designed and manufactured an adjustable bra to fit breasts of different sizes (Anisomastia). Anisomastia is called the visible asymmetry of the breast and it is something that is found in a very large percentage of women. This new bra had air channels (pneumatic system) inside in order to change its size on each side. A sensor was used to control the air pressure, which in turn adjusts the size. The result of the proposed product was the elimination of breast imbalance during its use. The design process was based on the shape of the muscle tissue in the area, in other words to hold the breast. The construction process started with the 3D scanning procedure of the area and the creation of a prototype geometry out of cardboard on a 1:1 scale. The final shape of the bra was defined through Grasshopper™. Computational design based on the 3D scanned geometry was used at the beginning, while molding followed as a manufacturing process. Sareen et al. [51] built 3D inflatable objects using textile plastic films. Using computational design tools, 2D flexible plastic surfaces of closed volume were manufactured. Based on the shape, they could acquire a 3D geometry when air was introduced inside them. With the use of a special machinery and the simulations performed, the two flexible surfaces were joined circumferentially through thermoplastic welding. During welding, the various folds of the film defined the areas in which the object curved. As part of this research, various original constructions were made available, some of which could be worn on the human body. The presented method led to the motion creation in objects, without the use of mechanical parts but with only the controlled air pressure.

Markvicka et al. [52] presented a holistic fabrication of a human wearable electronic patch (ElectroDermis™). The electronic bandage could incorporate various sensors. This particular type of device was able to be placed in various areas of the human body. The entire process was automated through Rhinoceros™-based computational design programming code and the Human UI™ plugin. The manufacturing process begun with the 3D scan of the selected body area and continued with the processing and conversion of the 3D surface into a 2D shape within Rhinoceros™ CAD system. The result of the computational design was the contour of the electronic bandage. Based on the outline, the ElectroDermis™ was manufactured, into which the corresponding electronic sensors are inserted. ElectroDermis™ consists of several layers of materials so that it can hold all the electronic components it contains. At the end, with a medical-type adhesive, the electronic bandage is placed and stuck to the human body. Various examples of applications of ElectroDermis™ are presented, i.e., forehead and temperature mask, vitals monitor and food-detection necklace.

Wang et al. [53] presented a case study of prosthetic makeup combined with computational design. The wearable makeup, namely Morphase, aimed towards the best and highest quality appearance of human expressions using modern technologies. The research was divided into three main stages: (a) scan the face and manage the 3D model using computational design, (b) create the negative mold of the prosthesis based on the results of the computational design (3D printer and manufacturing the Morphase prototype with silicone was used) and (c) painting the Morphase prosthetic by hand based on the outlines produced digitally.

Cheng et al. [54] performed 3D printing by combining two different materials in order to bend and curve the final geometry. The main idea of this research was based on how a growing plant can be curved to embrace any geometry without any mechanical component. Ambient humidity has the ability to change the size of a material. According to this characteristic, a combination of two different materials was carried out, which, if printed together in two different layers, the final geometry curves appropriately when it comes in contact with water. The role of computational design was to translate and import the nature-inspired techniques into a computer visual programming language. The output of the code produced could create the formation required to curve the final geometry in a controllable manner. The two materials used were wood-polymer (WPC) as the enabling material and ABS as the restraining material. After several experiments, a prototype implementation of a wrist splint that could be wrapped around an arm was built. Finally, an evaluation of the final result was performed by reverse engineering using a 3D scan of the curved geometry.

Bai et al. [55] developed a parametric method for automating the design of products worn on a person's face and head. Computational design was used with an aim to create customized personalized wearable products. With the use of 3D scanning technologies, various measurements related to the geometry of the head were collected. Based on these measurements, the algorithm used designed the geometry of each product according to the customer's anthropometric dimensions. The result of this process was the automation of designing specialized wearable products. As part of the research, a case study was also carried out, in which the goal was the design of gills. Three different methods were performed and evaluated for head scanning. The final design produced by the algorithm was 3D printed. The final product was evaluated with positive comments after its use. It proved to be comfortable and perfectly integrated into the anatomy of the face. Fernandez-

Vicente et al. [56] implemented an algorithm for the production of facial glasses according to the anthropometric characteristics of each user. An automated design process was depicted using computational design. The application collected and processed head scan data received from photogrammetry. The designer then needed to set some control points, on which to base the dimensions of the final product. A prototype of the geometry was built using a 3D printer in order to minimize the fabrication costs.

EL-Kholy et al. [57] incorporated parametric designs into garments using modern technologies and tools such as 3D printing and computational design. More specifically, three versions of Islamic motifs were developed in various types of women's clothing. The design of the Islamic motifs was carried out using computational design based on Grasshopper™ visual programming language. The final designs of the parametric geometries were fabricated using 3D printing and attached to three garments. The design and manufacturing steps, as well as the Islamic motifs and their design significance were described in a detailed manner.

Greder et al. [58] designed clothing using a combination of computational design and novel fabrication technologies. The research presented details both the design process of a woman's garment and its manufacturing methods. Specifically, the garment was a corset, so it could adapt evenly to the curves of the body. The design process began with digitizing the user body geometry based on a 3D scanning procedure. Then the computational design tools modeled the appropriate complex geometries on the digital body. The way the geometries were formed allowed the morphology of the garment to adapt to the user body. At the end, a 3D printer fabricated the actual prototype, which was tested on the users' body.

Nachtigall et al. [59] delivered a case study on designing a customized shoe with computational design tools. This study involved a collaborative work among three designers (a fashion designer, an interaction designer and a shoe design researcher). The goal was to create a shoe which by design can adapt and follow the movements of the user. In particular, reference was made to a 4D printing geometry, which allowed various movements and bending during its use. Beyond the functional part, the shoe provided the user with comfort, aesthetics and robustness while walking. A 3D scan of legs was performed to design the geometry, followed by various computational tools focused on the development of the geometry. Several 3D printing design iterations were used for creating the final geometry. In each repetition, a record was made with the difficulties and problems faced, and how they were tackled. This process was repeated until the final product was presented.

Efkolidis et al. [60] designed and manufactured jewelry using computer-aided design. The main objective was to create unusual jewelry geometry. The algorithm built in Grasshopper™ could produce different variations of the jewelry geometry in a short period of time. The basic shape of the jewel followed the Möbius Strip. At the end of the process and after creating several variations, a real prototype ring was created using an SLA 3D printer.

Sun et al. [61] built a method of creating products with a 3D printer, emphasizing the design process and outcome. One of the main goals was to reduce the weight of an object and, by extension, to reduce both the material needed and the total cost. Computational and parametric design were used to find the optimal paths of a volume when creating the mesh. The output of the final code required a solid 3D object and through various variables could automatically map it to a mesh-based geometry of the same shape and size. Then, based on the produced code, various prototypes were manufactured, i.e., wristband, armband.

2.3.2. Health-Based Applications

Li and Tanaka [62] built a system for creating a hand orthosis with a series of automated tools. The aim of the study beyond the creation of the system was the search for advantages, limitations as well as solutions, when using the system itself. It did not differ from other similar methods as it started with 3D scanning, continued with the design algorithm and ended with 3D printing. The differentiation of this particular system was that the process was divided into five stages so that possible problems could be found and solved before reaching the final geometry. Also, in the automated design stage, various parameters had been added with which the operator (medical staff) could define a number of characteristics such as the thickness of the geometry, its density as well as the mesh-based structure. At the end of the study, the finite element method was used for evaluating the structural strength of the geometry. At the same time, a test was carried out by various users who evaluated the whole process positively. Barros et al. [63] designed a wearable hand orthosis based on the origami principles together with computational design tools. This particular orthosis was designed and developed digitally based on the 3D scanned geometry of the user's hand. The feature of origami allowed the generation of a flat surface geometry, which could be folded onto the real hand. The chosen origami design came from Yoshimura as it had the ability to be stabilized into a rigid structure when creating a closed geometry. The feature of creating a planar geometry led to the use of 3D printing technology for fabrication, and the material stiffness after folding into a cylindrical shape allowed it to be used as a hand orthosis. Buonamici et al. [64] built a system with an aim to automate the design and fabrication of an orthosis for hand fractures. The system consisted of a 3D scanning device, an algorithm to automate the steps involved and a 3D printer that fabricated the final orthosis. The 3D scanner used photogrammetry and converted the geometry of the hand into a 3D digital form. Next, the algorithm further processed the data involved and created the geometry of the orthosis, which finally was 3D printed. The principal of the system was to enable its use by medical personnel. The system was tested successfully by the appropriate medical staff with limited experience in 3D technologies.

Li and Tanaka [65] presented a parametric system for producing 3D geometries as orthoses for hand fracture repair. An orthosis design generator was implemented in order to reduce the design time. The design algorithm used a Visual Programming Language in the CAD environment in order to automate the commands needed. The process started with the 3D scanning of the respective part, continued with the processing of the available data, thus designing and 3D printing the resulted geometry. The algorithm was tested by medical doctors, who had no experience in the technologies involved and manage to create effective final 3D models. Zhang et al. [66] developed a computational design system in order to produce orthosis geometries for different regions of the human body. The purpose of the study was to create an appropriate geometry that allowed the control of the corresponding area temperature. At first, a 3D scan was performed for recording the local body temperatures using an infrared camera. Then the data of the scan and the selected temperatures were processed by an algorithm, which effectively designed the 3D geometry. Temperature control was achieved through the lattice design of the orthosis, which was based on the Voronoi pattern. The algorithm based on the thermal images defined different densities in the geometry of the orthosis. The effect of different local densities allowed or prevented the insertion of ambient air into the orthosis and as a result the temperature was controlled. Three prototypes were tested on volunteers. The test results proved that the change in the orthosis density percentage could affect the local temperatures.

Kumar and Chhabra [67] developed a parametric system for the fabrication of an orthosis for finger fractures. The aim of the study was to create a parametric design system for the automation of an improved finger orthosis. The study used a 3D scan of the hand in order to digitize the morphology of the struck finger. The parametric system combined with the artificial intelligence was able to make a new orthosis geometry improved over previous designs. The algorithm performed a transformation of an initial geometry. With this particular technique, the removal of unnecessary weight was achieved without greatly affecting the mechanical properties of the geometry. Badini et al. [68] made available a parametric application for the design and manufacture of a hand orthosis. The target population of the study was patients with Motor Neurone Disease (MND). The main problem of these patients was muscle atrophy of the hand and wrist. For this reason, this specific study aimed to design a hand orthosis that allowed controlled certain movements of the injured hand. More specifically, two lattice structures were developed, which then were evaluated about their mechanical behaviors using finite elements. One of the two structures presented improved controlled results as it maintained a more symmetrical and uniform morphology. Then, using a 3D printer, some prototypes were tested. At the end of the study, short interviews were conducted with patients with motor neurone disease in order to provide feedback on the application. Table 5 schematically depicts the Computational Design-related papers used in this paragraph.

Table 5. Definition of the research in the category Computational Design (Co De).

<table>
<tr><th>3D P</th><th>Anthro</th><th>Co De</th><th>Kine</th><th>Foot</th><th>Health</th><th>Smart</th><th>Athle</th></tr>
<tr><td colspan="4">Design Advancements</td><td colspan="4">Health-Based Applications</td></tr>
<tr><td colspan="2">Researchers</td><td colspan="2">Keyword</td><td colspan="2">Researchers</td><td colspan="2">Keyword</td></tr>
<tr><td colspan="2">Urquhart et al., 2022 [49]</td><td colspan="2">Parametric design</td><td colspan="2">Li and Tanaka, 2018a [62]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Lazaro Vasquez, 2019 [50]</td><td colspan="2">Body measurement</td><td colspan="2">Barros et al., 2022 [63]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Sareen et al., 2017 [51]</td><td colspan="2">Body measurement</td><td colspan="2">Buonamici et al., 2020 [64]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Markvicka et al., 2019 [52]</td><td colspan="2">Body measurement</td><td colspan="2">Li and Tanaka, 2018b [65]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Wang et al., 2022 [53]</td><td colspan="2">Body measurement</td><td colspan="2">Zhang et al., 2017 [66]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Cheng et al., 2021 [54]</td><td colspan="2">3D/4D printing</td><td colspan="2">Kumar and Chhabra, 2023 [67]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Bai et al., 2021 [55]</td><td colspan="2">Body measurement</td><td colspan="2">Badini et al., 2023 [68]</td><td colspan="2">Auxiliary tool</td></tr>
<tr><td colspan="2">Fernandez-Vicente et al., 2016 [56]</td><td colspan="2">Body measurement</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">EL-Kholy et al., 2021 [57]</td><td colspan="2">3D pattern</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Greder et al., 2020 [58]</td><td colspan="2">3D/4D printing</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Nachtigall et al., 2018 [59]</td><td colspan="2">3D/4D printing</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Efkolidis et al., 2020 [60]</td><td colspan="2">Parametric design</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Sun et al., 2021 [61]</td><td colspan="2">Parametric design</td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

2.4. Human Body Kinematics

Tsabedze et al. [69] designed a wearable robotic hand device that can move the user's fingers in a different way. The robotic device consisted of a glove, four motors (actuators), wire cables to transfer motion as well as Force-Sensing Resistor (FSR) pressure sensors. The operation of the device was via the combination of assisted movement and resistive contact through the sensors. The paper presented the design process as well as the design decisions made during the project. The results after using the prototype built were very encouraging, while further work was proposed.

Malvezzi et al. [70] designed and presented a portable exoskeleton that can be worn on the fingers of the user's hand, in order to provide quick and proper rehabilitation after an injury. The device used a simple kinematic chain for each finger to which a single motor corresponded. In this way, the user could move each finger separately. The aim of the device was to reduce the weight and increase the reliability of the movements compared to other similar devices. With the use of sensors, the device recorded the movement effort of each finger and then assisted it with the corresponding motor. Key future goals achieved were to extend the device to the entire hand as well as a series of experiments to better control and evaluate the device.

Liu et al. [71] presented a wearable device using an alternative type of sensor in order to record the finger motions. In other studies, the motion recording devices failed to record all directions of every case as well as the variable wearable microclimate. In this study, an easy-to-assemble motion capture network was used based on MWCNT carbon nanotubes. These sensors were very sensitive when recording the changes in the microenvironment, therefore they could record phenomena such as temperature, humidity percentage and various others. They could also record the change in size, pressure as well as the bending of their geometry. The sensors were then successfully attached to a glove for further testing. One possible application of such a device could be the motion recording for human-computer communication.

Kim et al. [72] made available a leg exoskeleton in the ankle area with integrated wearable flexible bioelectrical systems. The study focused on a device aiming at estimating metabolic cost and physical effort. The recording of the data was achieved using special sensors as well as the exoskeleton to record the movements. The device managed to collect data from people while performing various processes. In more detail, the device was tested while walking, running and squatting. The whole system successfully fulfilled its objectives, resulting in the possibility of further developing the system in the future.

Chirila et al. [73] presented a device with the ability to interface man and a machine. The interface device was worn on a human hand and could remotely control a five-finger robotic hand. Using 3D printing, a flexible glove was created in which the elongation sensors were placed. The aim of the device was to be light enough, able to breathe and to maintain the elasticity of a glove. The 3D printed material used was Thermoplastic Polyurethane (TPU), which was flexible enough to adapt to the hand. The recorded data of the glove device was sent to a host computer, which in turn gave the corresponding commands to a robotic arm. A Finite-Element Analysis (FEA) was successfully carried out with an aim to simulate the desired movements.

Cempini et al. [74] designed and fabricated a wearable robotic device that could be worn on the lower end of the hands. The main goal of the research was to restore the movements of a person's fingers after a stroke. The wearable device was fitted on the hand and had the ability to control the two main fingers (thumb and index). The design of this particular exoskeleton was based on a novel kinematic design that allowed its use in different hand sizes. The position of the actuators (i.e., the motors) was far from the device and they transmitted the movement with a Bowden cable in order to reduce the weight and volume of the device. At the end, a prototype was built and the appropriate controls were tested.

Wu et al. [75] implemented a flexible exoskeleton to assist the movement of a human's elbow based on neural networks. By using various sensors, the device could record the movement intention and then assist it. The device consisted of three main parts. The first part was the soft wearable glove, in which the rest of the components were placed. The second part was the motors for activating the movement, while the third part consisted of the transfer of the movement, i.e., from the elbow actuator. Various experiments were carried out involving five volunteers, under different anthropometric parameters. The results of the experiments proved that a higher assistance of the movement was achieved, compared to other methods. Reducing the weight and improving the mechanical structure of the system were the next aims for this project.

Chen et al. [76] built a portable rubber robot for a patient with upper limb dyskinesia in order to restore his/her movement. Upper limb dyskinesia is a common problem that can occur after a stroke, car accident or sports injury. The purpose of the device was the rapid recovery of the functions of the affected joint. The device could be worn on the hand like a glove and used pneumatic actuators to create the movements. More specifically, there were some cysts (air chambers), which could be inflated in a controlled manner by introducing air. The reason for choosing this type of actuator was the increased safety of the device. The prototype built was tested on patients for wrist dyskinesia rehabilitation training. The device was tested and analyzed without any particular problem arising. Also, after its use, no secondary injury occurred to the patient, so the final outcome was that the rubber robot was safe for further experimentation.

Abdallah and Bouteraa [77] designed a portable device for rehabilitation treatments. It was a hand exoskeleton whose goal was to restore hand movements to people who had suffered a stroke. In these people, frequent hand movement are important as they are likely to acquire motor disfunctions in their limbs. The wearable robotic exoskeleton controls movement intentions were based on electromyography (EMG). The final decision and execution of the movements was carried out with the help of the Robot Operating System (ROS), which was responsible for the connection between the nodes. The original construction created by 3D printing technology using PLA filament.

Allen d′ et al. [78] developed a soft wearable robot that can guide the movements of the lower limbs according to the rhythm of a song. In essence, an exoskeleton built into a garment was introduced and assist a dancer by instructing the movements to be made. While using pneumatic actuators, the device was able to communicate with the dancer. The intensifiers were connected to closed chambers in which, when the air enters, they create a movement both for the exoskeleton and the dancer. After the build of the prototype, a number of experiments were led with the participant dancers. It was evident that although the device may limit the movements to some extent, it can inspire them with new dance moves. It was also mentioned that with such technologies the choreographer can intervene directly and effectively in the movements of the dancer. In essence, a visual stimulus during a dance lesson can be turned into a physical movement from the teacher to the student.

Balaji et al. [79] presented a portable skeletal structure that could replace the use of the chair with a partial standing posture of the body. This device was an exoskeleton that adapted to the legs of a person who had to stand for several hours of the day. Due to the structure of the exoskeleton, if the user bent their legs slightly, the weight of the body was transferred to a damper and then it was transferred directly to the ground. The user who was wearing the device could relax the muscles of his legs, because he did not have to support the whole weight of his body. In fact, with this device the user could sit in a semi-upright position. Further to designing the device, a finite element analysis was performed to assess its fitness for use. Then a prototype of the exoskeleton was made for actual testing and evaluation. The weight of the device was 1.84 kg for each leg.

Ou et al. [80] designed a portable exoskeleton to reactivate the upper limbs of a person after a hemiplegic stroke. The purpose of the device served the fastest recovery of the patient. The wearable exoskeleton fitted the patient's hand and by the use of electric motors a kinematic mechanism could move all the fingers of the hand individually. The device was entirely manufactured using 3D printing technology, as this significantly reduces the cost and time of fabrication. The device was given to various organizations, such as hospitals, for use on real patients in order to optimize its design.

Chen et al. [81] built an exoskeleton suit with an aim to assist the standing movements of paralyzed patients. The aim of the device was the balance of the patient both in a stable position and while walking. The exoskeleton suit was worn over the entire body and focused on the hip joints as well as on the knees. The design of the suit was carried out in such a way that it was ergonomic, easy to interact with the user, safe and comfortable. With the use of a smart phone app, the device could communicate with the patient as well as record various data. A number of clinical tests were carried out with paralyzed patients, where they were able to stand up and walk without any particular problems.

Long et al. [82] developed an exoskeleton system aimed at patients who have injured one of their two lower limbs. The device resembled an exoskeleton that was worn on the body and used two methods of patient rehabilitation. The hybrid system incorporated a passive and an active operation of the device. The device initially used the passive function until the injured limb was fully restored. This mode could also be called passive training. The system perceived the rehabilitation of the injured limb by comparing it with the uninjured one (as far as their movements, reactions and walking trajectory were concerned). After the restoration, the device entered into its active operation so as to fully recover the injured limb following the trajectory and movements of the healthy limb.

Liu et al. [83] developed a portable exoskeleton for training the muscles of a person's upper limbs. The device used EMG (electromyography) electrodes and by reading the muscle signals could predict the movement the user wanted to make. Then the device enhanced the human movement. The device was worn on the upper body and could be adjusted to both hands. It could also perform two active and two passive movements based on the mechanics of the structure. While experimenting, the movements that each user tried to perform were achieved. More work could be conducted in improving the movement control method.

Cappello et al. [84] designed a soft exoskeleton for the upper limbs of a human. The aim of the exoskeleton was to assist elbow movements using an electric motor. The transfer of the movement from the motor to the device and by extension to the elbow was performed using a Bowden cable. Two Bowden cables were connected to the motor shaft with opposite torque. In this way, the device was enabled to both activate and restore elbow movement. The final design of the soft exoskeleton was realized in a prototype built and evaluated during its use.

Emmens et al. [85] designed a wearable exoskeleton as a balance device for people with spinal cord injury. This specific exoskeleton was applied to the patient's leg and had an effect on the knee and ankle bend to achieve the balance of the body. Two balance controllers were used to test the device. The first controller recorded the body sway and acted on the exoskeleton, while the second recorded the body's momentum. The two types of controllers were applied to three users with a spinal cord problem. In these balance experiments, each person stood upright and another person pushed them using a push stick. The goal of each patient was to regain balance without taking a step. The results of the experiments showed that with the use of the controllers, significant improvement was observed.

Ji et al. [86] fabricated a portable exoskeleton that adapts to a human body in order to assist in lifting objects from the ground and avoid various musculoskeletal conditions. The objectives of the study were, first, the correct human-machine interaction in terms of the movements, and second, the correct placement of the exoskeleton on the human body. The device consisted of bandages that adapted to the back, a lumbar back support, hip joints, leg connections and mechanisms that were adjustable to the individual human body. In the area of the hip joint a motor was included for assistance. The exoskeleton was tested with success and proved that there was a significant assistance in lifting loads.

Zhao et al. [87] built an upper limb exoskeleton for remote control of humanoid robots. In this study, a teleoperation technology was developed that combines the control of both force and precision of a robot's movements. The main problem with traditional robot control methods was the special environments required as well as the bulky mechanisms. This exoskeleton was a passive device that was placed on the operator's shoulder. Movements performed by the operator's upper limb were mapped and sent to the humanoid robot. After testing the system, no failure occurred in the mode of operation. At the same time, the manipulation of the robot was characterized as an easy process in the areas of the normal range of motion of the hand. Table 6 schematically depicts the Human Body Kinematics-related papers used in this paragraph.

Table 6. Definition of the research in the category Human Body Kinematics (Kine).

3D P	**Anthro**	**Co De**	**Kine**	**Foot**	**Health**	**Smart**	**Athle**

Part 1/2		Part 2/2	
Researchers	Keyword	Researchers	Keyword
Tsabedze et al., 2022 [69]	Robotic technology	Balaji et al., 2018 [79]	Auxiliary tool
Malvezzi et al., 2020 [70]	Auxiliary tool	Ou et al., 2020 [80]	Auxiliary tool
Liu et al., 2022 [71]	Robotic technology	Chen et al., 2017 [81]	Auxiliary tool
Kim et al., 2023 [72]	Sensor system	Long et al., 2016 [82]	Robotic technology
Chirila et al., 2020 [73]	Robotic technology	Liu et al., 2017 [83]	Auxiliary tool
Cempini et al., 2013 [74]	Robotic technology	Cappello et al., 2016 [84]	Auxiliary tool
Wu et al., 2019 [75]	Auxiliary tool	Emmens et al., 2018 [85]	Auxiliary tool
Chen et al., 2022 [76]	Auxiliary tool	Ji et al., 2020 [86]	Auxiliary tool
Abdallah and Bouteraa, 2023 [77]	Auxiliary tool	Zhao et al., 2023 [87]	Robotic technology
Allen D' et al., 2022 [78]	Robotic technology		

2.5. Footwear

Kiernan et al. [88] evaluated and compared various methods of tracking steps during human running. In this study, 18 different tracking methods with the common feature of using a wearable accelerometer and/or gyroscope were compared. Footstep tracking was related to initial and final foot contact with the ground versus time. The tests of each method were carried out on 74 runners under specific conditions with the aim of searching for and quantifying the errors of each of them. At the end of the study, conclusions were drawn regarding the most reliable methods in relation to the corresponding running conditions.

Pineda-Gutierrez et al. [89] designed a pressure calculation system of the foot surface using a special sole in order to analyze the walking steps. The system consisted of a special sole that included sensors, a microcontroller (data management) and computer software that received and displayed the corresponding measurements. The sensors used in the sole were pressure-sensitive FSR-type (Force Sensitive Resistor). The seven sensors were placed in a specific way on a thin surface that had a sole-like geometry. This surface was placed on the inside of the shoe. The microcontroller was placed around the ankle so that it was close to the sensors but at the same time did not interfere with walking. The software received the pieces of information from the microcontroller using Bluetooth technology. The whole system could perform two measurement processes: static and dynamic. The first measurement process was implemented when the person was standing still, while the second was implemented during walking. In the second process, walking was divided into discrete walking cycles. After various tests, the system showed remarkable operation and pressure-recording ability.

Zrenner et al. [90] recorded running data using a sensor inside the runner's shoes. The aim was to improve the design of shoes used for running. By inserting a sensor in the area of the sole, the angles at which a shoe hits and leaves flat ground were calculated. As part of the research, a number of device tests were carried out by 27 volunteers. In the measurements, 5112 contacts with the ground were calculated. A relevant algorithm was created for the processing and management of all data. Some of the features of the algorithm were the alignment of the sensor to the shoe and the ground, the separation of the step into several segments and the calculation of angles. The future work planned were to upgrade the sensor so that it could measure speed, distance as well as terrain evaluation.

Sazonov et al. [91] designed a wearable system to monitor the pressure distribution of the feet in various activities. The system consisted of a set of pressure sensors and an acceleration sensor. All the sensors as well as the microcontroller of the system were placed in a shoe. This wearable system could evaluate the data recorded and perceive the condition the user was in at the time. The device's algorithm could record six different situations such as standing, sitting, climbing and descending stairs, cycling and walking/jogging. The results of the device, when compared to other devices offered, showed increased accuracy in recording the correct state of the user. The low cost of the device combined with the high accuracy of the recording condition offers great potential for future work. Nagamune and Yamada [92] presented a system for measuring the pressure of the foot and calculating the center of pressure (COP). This system was designed to be used in sports activities so its weight and size was kept to a minimum. The device consisted of the sole with the corresponding pressure sensors and the microcontroller for recording the measurements. The device was tested on healthy subjects in straight gait, rotational gait and vertical rotational gait. From the results of the measurements, it was evident that there was a difference in COP between the walking modes so the device could be used by professional athletes as well.

Ryu et al. [93] applied a piezoelectric wearable device on a human foot for energy generation and signal detection. First, an Inner-Electrode Piezoelectric Yarn (IEPY) piezoelectric filament was created. The thread consisted internally of a conductive fiber, while externally of a polymer in the form of a coating. After the thread was built, it was placed in various ways at the bottom of a sock. From the test results, it appeared that the specific thread had the potential to be used in applications for monitoring steps and other exercises with a wide range of applications.

Tahir et al. [94] compared three types of sensors for recording a person's walking data. The three sensors were compared in recording the pressure using different methods (FSR sensors, piezoelectric ceramic sensors, piezoelectric flexible sensors). All three types of sensors were fitted to three different soles with an aim to evaluate their recording results. Before testing, the sensors were calibrated using a standard precision balance. From the results of the tests, it emerged that the use of FSRs had more accurate results than the other two types used. In addition, the piezoelectric sensors showed high-quality recording samples as references to the start and end of the movement at each step. Amitrano et al. [95] designed a wearable system that was worn on a patients' leg to monitor how they walk. The system consisted of a set of fabric sensors and special cables, which were integrated into the surface of a sock. The system also had a unit for recording and transmitting data to a fixed device wirelessly. The tracking device could perceive signals of angular velocities and plantar pressures of each foot. An experimental stage followed with three volunteers to whom the specific system was adapted and their measurements were validated.

Kimura et al. [96] made available a system for recording foot loads. The recording system that was built used triaxial stress sensors, which were placed on the foot of a person. The use of these sensors facilitated isolating the pressure and shear measurements of the leg from external factors. The small size of the sensors contributed to their load ability, with the result that the measurements during walking were in a natural state. The data recorded by the sensors was stored on a memory card via a microcomputer. The data were then transferred to a computer for processing and evaluation. In this way, the use of cables between the human and the computer was avoided, which could create problems while walking. At the end of the study, tests were carried out and the validity of the whole system was confirmed. The study concluded that the use of this monitoring system could help rehabilitation as well as sports medicine.

Cheng et al. [97] implemented a surface-shaped triboelectric generator that was integrated into the sole of a shoe to generate energy. Electricity was generated by the friction created in every human step. A thin surface of porous ethylene-vinyl acetate copolymer (EVA) was used to create the triboelectric generator. This particular device differed from others as it used the human body as an electrode. After various measurements, it was evident that after every step of an adult there was an output voltage of 810V and a transferred charge of about 550nC. Finally, the system was connected to a group of LEDs that lit up during walking. Possible applications of this device include powering both portable electronics and implantable devices. Su et al. [98] presented a wearable Triboelectric Nanogenerator (TENG) embedded in the sole of a shoe. A key feature of the device was the way in which the connection was made through the ground and the human body. The goal of the portable device was to produce and store electricity as well as convert it into a human motion sensor. Through testing, the maximum energy produced by the device was calculated to be 946 V and a short circuit current of 36.3 µA. The second function of the device related to the recording of movements enables the user to record the gait, the number of steps as well as the calculation of the speed during the gait.

Liu et al. [99] designed a shoe sole with an aim to achieve maximum absorption of ground vibrations. More specifically, using computational design, a form of sole was created with four different schematic structures (cross structure, diamond structure, star structure and X structure). The aim was to compare the different structures using finite element analysis. In the schematic structures, three different thickness values were defined, resulting in the creation of 12 different variations for carrying out the tests. As a result, the structure with the greatest shock absorption was the diamond structure, as it presented the greatest elasticity and energy absorption in each impact energy.

Manavis et al. [100] presented an automated system for the design of shoe soles based on anthropometric data. The system processed pressure data acquired using color images and scan data using 3D geometry. The output of the algorithm was a 3D sole structure that varied its density based on recorded pressure. The structure was built on a technique called Voronoi. The result incorporated the automation of the design together with the adaptation of the dimensions and characteristics of the sole to the user. A prototype of the sole was fabricated and early evaluation was performed using 3D printing technology.

Amorim et al. [101] built a shoe sole based on meta-material structures (MMS). The goal was to create a sole that could accommodate various structures inside. The correspondence of the structures in each area of the sole was defined by the use of computational design. Each structure could be repeated in the corresponding area as well as connected to its neighbors. It is important to mention that the process of defining the structures was based on the pressure exerted on each area. The algorithm could record the areas of the foot where the most pressure was applied. The result of this study was the creation of a prototype sole with different mechanical properties using 3D printing technology.

Ishiguro et al. [102] built a system for wireless control of a humanoid robot by a user. The study dealt with the control of the lower part of the robot, which was facing balance issues. The aim of the system was for the bipedal robot to imitate the movements of a human. Two devices were created and adapted to the user's legs. The two devices were shaped like an open shoe and included various sensors inside. When wearing the two special devices, the user was able to transfer the spatial and rotational perturbations of his feet to the robot, with immediate response. Table 7 schematically depicts the Footwear-related papers used in this paragraph.

Table 7. Definition of the research in the category Footwear (Foot).

3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle

Part 1/2		Part 2/2	
Researchers	Keyword	Researchers	Keyword
Kiernan et al., 2023 [88]	Sensor system	Kimura et al., 2023 [96]	Sensor system
Pineda-Gutierrez et al., 2019 [89]	Sensor system	Cheng et al., 2015 [97]	Triboelectric
Zrenner et al., 2018 [90]	Sensor system	Su et al., 2023 [98]	Triboelectric
Sazonov et al., 2011 [91]	Sensor system	Liu et al., 2020 [99]	3D pattern
Nagamune and Yamada, 2019 [92]	Sensor system	Manavis et al., 2022 [100]	Measurement optimization
Ryu et al., 2022 [93]	Sensor system	Amorim et al., 2019 [101]	Metamaterial
Tahir et al., 2020 [94]	Sensor system	Ishiguro et al., 2016 [102]	Sensor system
Amitrano et al., 2020 [95]	Sensor system		

2.6. Health and Safety

2.6.1. Equipment Design

Bukauskas et al. [103] designed a face mask against infections, which was built with origami techniques. The mask was made using a flat transparent surface, which when folded a certain way could be curved and could be worn by a person. The use of computational design tools led to parametrically design such folded masks with a great deal of geometrical alternatives. Following the proposed methodology, a parametrically developed design could fit to the majority of the population. Before testing the actual models, a digital evaluation was carried out using 3D head scans. Nilasaroya et al. [104] designed and built a protective face shield against infections. This was a secondary protection solution after using a suitable face mask. The target audience consisted mainly of healthcare professionals. It is important to mention that the objective was the creation of tens of thousands of shields. In more details, this study presents the materials as well as various design issues of the shield during its fabrication. Also, tests were carried out on various types of impacts in order to check the mechanical properties of the shield. At the same time, comparative tests were carried out with other corresponding traditional face shields. Suen et al. [105] fabricated an innovative face mask design to prevent infections with built-in air conditioning and manage the indoor microclimate. With the use of the proposed mask, the internal increase in air temperature was avoided and thus breathing difficulties and various health problems were omitted. The mask used a Thermoelectric Cooler (TEC) and ventilation unit (fan) to manage the internal temperature. Also, the design of the mask had a specific path for the oriented direction of the air. Based on the new design, a prototype product was evaluated. From the results of the various evaluation measurements, it emerged that there was a noticeable reduction in the internal temperature and humidity. Iftikhar Hashmi and Luximon [106] studied a face mask to prevent infections with an emphasis on aesthetic design. Apart from the aesthetic part of this product, its reliability and functionality played an important role. The design of the new mask consisted of a support and an outer casing of a normal medical type mask. During the design there were four main goals, i.e., comfortable breathing, comfort, ease of use and reusability. Regarding comfort and ease of use, the newly designed mask would not rest on the ears or behind the neck, but would fit perfectly on the face based on its ergonomics. The first stage of the design was based on the 3D scan of the face. Then final geometry was 3D modeled and then 3D printed. The printing material used was ABS and by applying a thin layer of silicone, the support of the mask on the face was achieved. The normal medical type mask was attached to the printed object.

Liang et al. [107] built a device, printed by a 3D printer equipment, with the ability to administer a medicine in the oral area. This product could be used for various oral diseases. The geometry can cover a portion of the teeth. After 3D scanning the area and 3D printing the device, the various drug substances in the oral area could be realized. A number of successful experiments were carried out for validation purposes.

Laffan et al. [108] studied a suit worn by a firefighter for easy navigation in the target area. Initially, the research was carried out on the already existing technology followed by the design of the suit system. The suit was able to send the appropriate location data via a set of equipment (GPS, microcontroller, etc.). The system then checked if the firefighter's direction was correct and sent heading-correction data. The firefighter, through local vibrations in his body, would understand in which direction he should go. Jeril and Sarath [109] carried out wireless monitoring of the firefighters' health and stress during their work using a wearable device. The sensors were integrated into the firefighter's glove and were able to record the person's heart rate and blood pressure in real time. By sending the health data to the headquarters, the status of the firefighter was reported. The job of a firefighter is one of the most stressful jobs performed and future upgrades of this system are expected. Zhang et al. [110] developed a smart helmet for firefighters with an aim to control their health during firefighting in severe conditions. A potential health problem for them was dehydration. The smart helmet with the appropriate sensors would be able to record the body's dehydration rate and update a host computer wirelessly. The sensors of the smart helmet consist of a thermostat, a heart rate recorder and a motion recorder. As part of the study, the communication software between the helmet and the main computer was created, as well as a mobile application in which the history of the measurements would be recorded. Finally, an evaluation of the system and the device was carried out by firefighters for the evolution of the smart helmet.

Tartare et al. [111] designed a garment for firefighters with built-in sensors to monitor health (fatigue, stress) during work. The main difference of this application from other similar ones was that the firefighter did not need any external accessory, on the contrary, the device was already adapted to him. The garment's sensors were located at various points on it and all were connected to a central controller. All sensor connections were made using a conductive thread, which was sewn onto the garment. This system could record various body measurements and send them to a central computer for decision making. The garment was successfully tested and measurements were taken by a group of seven people (three women and four men). Park et al. [112] observed the effect of firefighter's wearables on the efficiency of the motion and balance. More specifically, the study tested boot height and Self-Contained Breathing Apparatus (SCBA) cylinder size in both tall and short firefighters. The two main hypotheses were: (a) whether its height affects the ease of leg motion, and (b) whether the size of the SCBA cylinder affects trunk and body movements. Based on the two cases, a survey was carried out with 21 firefighters who were asked to perform a series of specific exercises. The research results showed that the fixed boot height and fixed SCBA cylinder size could not support a wide range of users. The main parameter of the problem examined was based on the height difference of the firefighters. Van Kleunen et al. [113] implemented a navigation system for wildland firefighters. In essence, the use of wearable devices enabled the firefighters to head to the target point with the fastest route. Before designing the system, some constraints were defined, i.e., hands-free use of the system, low power consumption, ease of learning and reliability. The system consisted of three devices, one positioned on the helmet and two on the wrists. The helmet device used a microcontroller and a Global Positioning System (GPS) which could calculate if the direction of the firefighter was correct. In each mistaken direction followed by the firefighter, hand-based tactile feedback was provided (correction right, correction left).

2.6.2. Social Care Technology

Olson [114] conducted a review on the history of wearable sensors, how to manage data received from sensors and the modern health-monitoring devices. The various ways that a device could record various movements with an aim to recognize different activities (walking, running, standing, movements of falling) were examined. In addition, issues of estimating energy demand for these devices and the quality of the sensor operation for long term usage were tackled. An area of great interest could be the monitoring of various data from athletes. Callihan et al. [115] conducted research comparing three health monitoring methods. In recent years, there has been an increase in deaths and illnesses associated with high body heating as well as increased heart rates. The main objective of the study was to search for the correlation between the results from three monitoring methods. At the same time, the usability of the first method, which was the Slate Safety (SS) portable physiological monitoring system, was determined. The two other monitoring methods were a pill to swallow and a wearable heart rate monitor. Tests were performed on 20 nurses during their work routine using all three monitoring methods simultaneously.The data from each method were then compared. From the results of the comparison, a high correlation was observed between the three methods. The final conclusion of the study was that the use of the SS system demonstrated accuracy in both temperature measurements and heart rate measurements. At the same time, the device did not limit the movements of its users.

Sanfilippo and Pettersen [116] developed a system of various sensors for biometric and medical monitoring. It could be worn by a person on the chest area to monitor his health in real time. The device consisted of a set of sensors (electrocardiography sensor, temperature sensor, accelerometer), a motor (to create vibrations), a multi-colored LED lamp, an emergency button and a controller board. All of the above components were connected to the controller for measurements handling processes and then sent to a host computer. Warnings were initiated by applying vibrations and lights in case of occurring a problem with the user. With this system, the improvement of daily communication between doctors and patients was achieved. De Fazio et al. [117] studied a smart garment to monitor the health and environment of a worker in hazardous workplaces. The smart garment aimed to non-invasively collect data both from the human body and from the surrounding area for the safety and protection of its user. The smart garment incorporated a large set of sensors to record data such as heart rate, blood oxygenation and human body temperature. At the same time, the smart garment had the ability to collect information from the concentration of dangerous gases as well as the oxygen level of the surrounding space. The data were sent wirelessly to a cloud-based platform through which it was processed and stored. At the same time, the smart garment was energy independent as the energy required for its proper operation was produced through multiple energy sources it had. More specifically, the system was charged through light, through body heat as well as through limb movements. Through tests, the correct operation of the system was proven both in recording and sending data and in self-supplying its energy. Abbasianjahromi and Sohrab Ghazvini fabricated [118] a wearable device for the purpose of monitoring the proper functioning of personal care equipment. The incorrect use of personal protective equipment by the respective workers was often observed in workplaces. The aim of the study was to monitor the correct use of the equipment through the use of a wearable device. The wearable device was based on Internet of Things (IoT) since it incorporated sensors, used an internet connection, information processing and management, as well as utilized a smart phone application. The tracking device was used at various construction sites to collect the data. From the results of using the device, two main conclusions emerged. The first conclusion was related to the reduced use of protective equipment by workers at work. While the second conclusion was related to the non-use of the safety helmet by the staff. It was important to mention that there was no difference between skilled and unskilled workers in the way they used the equipment.

Xie and Wu [119] built an emergency kit to guide rescuers in performing Cardiopulmonary Resuscitation (CPR). It was a system that, through visual, audio and tactile signals, could help a non-specialist rescuer perform CPR on a person who had an emergency. The equipment had a device that used multisensory feedback. More specifically, the equipment consisted of three basic components which were the first aid clothing, an audiovisual system, and a vital signs detector. The main objective of the wearable device was to collect the patient's vital information and guide the CPR movements by a non-specialist who could play the role of a rescuer. As part of the study, the system was tested on 32 non-medical individuals, who were asked to execute the device's commands. Key criteria for evaluating effectiveness were chest compression depth and CPR execution rate. From the results of the tests, it appeared that the performance and correctness of the rescuers' movements were significantly enhanced, while at the same time the rescuers reported that the equipment was very easy to use.

Lin et al. [120] designed a wearable device that could be worn by a person with an aim to record their stress levels throughout the day. Traditional Electroencephalogram (EEG) modalities were extremely expensive and almost impossible to transport, making it impossible to perform a multi-hour check during the day. In this study, an approximate model of a wearable device that could record EEG signals was created. Then the aim was to create a connection between the EEG signals and the signals of an electrocardiogram when receiving data from volunteers. Based on the results, a polynomial regression model was implemented in order to accurately predict the stress scores.

Stetter et al. [121] implemented a wearable device with an Artificial Neural Network (ANN) for monitoring and calculating the forces exerted on the knee area during sports activity. The device incorporated an accelerometer and a gyroscope that were attached to the right knee and could record the movements of the athlete. At the same time, 42 spherical reflective markers were fitted to the human body, and could be recorded via cameras in order to digitize all the athlete's kinematic movements. The collected data were processed by an artificial neural network (ANN) with an aim to calculate the knee joint forces (KJF) during sports movements. As part of the study, various experiments were carried out to evaluate the system. From the test results, it emerged that the operation of the system showed significant agreement between the predicted results from the ANN and the corresponding calculated forces in most movements.

Di Paolo et al. [122] used inertial wearable sensors to monitor and evaluate recovery from an Anterior Cruciate Ligament (ACL) injury. An attempt was made to quantify and record the kinematics of the joint during rehabilitation and the recovery after the injury. In order to evaluate the inertial sensors, various stages of testing were carried out among 34 healthy athletes. During the tests, body movements were recorded simultaneously by two monitoring systems. The first monitoring system to be tested was called WIS (Wearable Inertial Sensors) and was a set of 15 inertial sensors. These sensors were placed in various parts of the body and recorded the various movements. The second tracking system was called OMB (Optoelectronic Marker-based) and was a set of 42 reflective markers on the body and 10 fixed cameras. The cameras recorded reflex indicators and digitized the human motion. When comparing the results of both the monitoring systems, it emerged that the WIS method had measurements that were largely consistent with the OMB method counterparts.

Matijevich et al. [123] conducted research using wearable sensors on the correlation between the ground reaction force and the load exerted on the tibia during exercise. Many athletes experience tibial fractures due to high stress accumulated from repeated impacts. This problem occurred after excessive exercise in horizontal and incline running. After several tests using 10 healthy subjects, the vertical ground pressures and the forces exerted on the shin area during running were measured. From the results of the tests, it emerged that, on average, there was no correlation between the two measurements. Therefore, using a wearable sensor to predict a tibia fracture was not a reliable and safe prevention method.

Xie et al. [124] presented a new low-cost wearable capacitive sensor based on a napkin for health monitoring. The sensor was fabricated through a simple process that used a paper towel, silver nanowires (NWs) and polydimethylsiloxane (PDMS). In this way, a mold was created in which the three materials were combined. The manufacturing process was repeated for the remaining side of the sensor. The two final pieces were joined together to form the final sensor. Through tests and measurements, it was proven that this new sensor had a very high sensitivity, as a result of which it could record heartbeat signals, finger movements and eyelid movements (opening and closing of the eyes). Zhao et al. [125] presented how to use a triboelectric surface made of polytetrafluoroethylene (PTFE) material in order to create wearable sensors and energy harvesting devices by recording electrical signals. The PTFE layer could be adhered to the human body using a double-sided surface adhesive tape. Although the human body was conductive, its effect was negligible on the device, a fact that was proven through various tests. Based on this triboelectric surface, three different applications of the PTFE surface connected to a microcontroller were implemented and presented. The initial two applications were related to the use of PTFE as a sensor. In the first case, the sensor could record the different surfaces when it came to contact with the human body. In essence, it could perceive and categorize a number of different objects in space. In the second case, the sensor could separate the signals it was receiving from the user and sent the corresponding information to a smart phone. In the last case of application, the PTFE surface was placed at the bottom of the sole and turned into an energy harvesting device. Gao et al. [126] built a highly sensitive microfluidic pressure sensor for recording and monitoring patient health. The sensor consisted of Galinstan microchannels designed according to the Wheatstone bridge circuit. The temperature in which there was a correct measurement received ranged from 20 °C to 50 °C. The high sensitivity was due to the very low-pressure detection limit which was below 50Pa. After the creation of the sensor, two applications were created for carrying out experiments. Initially, a polydimethylsiloxane (PDMS) wrist bracelet was manufactured with the sensor embedded on its surface. This bracelet could measure the user's heart rate very accurately. The second application was then developed, comprising a transparent PDMS glove which incorporated several sensors. This glove could record the pressure existed in different parts of the hand, when holding or touching an object. Picchio et al. [127] investigated a composite material named Eutectogels with which flexible sensors could be made to monitor a person's health. This composite material consisted of choline chloride/glycerol eutectic solvent, lignin sulfonate and gelatin. It offered very important properties such as flexibility, great adhesion and the possibility of 3D printing with a specialized 3D printer. Based on the high ionic and electrical conductivity presented by this material, various strain sensors as well as skin signals could be created. As part of the study, various sensors were printed with an aim to find the optimal properties. The final evaluation was carried out by creating sensors that were attached to the lower part of the wrist for electrocardiogram and electromyogram control. The results of the tests showed that the diagrams were in great agreement with the corresponding diagrams expected [128].

Kang et al. [128] studied a flexible sensor for monitoring pulse waves in real time. The monitoring of a person's health was often limited to specific places such as medical laboratories and specific time periods. Creating a wearable health monitoring device could record various data much more effectively and with great reliability, as it could check health indicators throughout the day. The device was placed on the user's wrist and consisted of a pressure sensor, signal stabilizer and micro-pressure system. The data of the sensors was collected by a microcontroller, where with the appropriate algorithm they were optimized according to the user. After several tests of the device, the results showed that the system was able to correctly perform the tracking process and quickly find the maximum pulse wave peaks in different people with an accuracy of 95%. He et al. [129] presented a flexible triboelectric surface that was adapted to the human body and could produce a higher voltage than other similar methods. The aim of the study was to improve the triboelectric performance so that it could be actively be used for charging wearable devices. A high-voltage diode as well as a mechanical switch were integrated inside a Textile-Based Triboelectric Nanogenerator (T-TENG) surface. The new triboelectric surface Diode-Enhanced Textile-Based Triboelectric Nanogenerator (DT-TENG) after testing showed 25 times higher voltage than the normal T-TENG. As a result, an application was presented where, using the DT-TENG surface, a device was created for communication between patients and doctors in a hospital setting. The device had six functions—commands with body movements. The location of the DT-TENG surface was used with an aim to generate energy from elbows, knees, foot soles, etc. Mahmud et al. [130] built wearable glasses to monitor a person's health and sent the data to a central computer. The glasses were fabricated using a 3D printer to incorporate various sensors and components. This device could record a person's heartbeat, movement, temperature, breathing and falling. All logged data were sent to a mobile app designed for this purpose using Bluetooth protocol. The mobile application processed the data and performed various actions if required. For example, in the event of a fall or human emergency, the authorities were immediately informed. Jinkins et al. [131] developed and created a novel material, based on which a device could be stabilized on the human body. This material could replace traditional ways of gluing (holding) portable devices for monitoring the health of patients in a hospital. The main problem with the previously used methods was the various skin irritations when removing a wearable device. The specific material consisted of a crystalline type of oil, which could change from solid to liquid form at a temperature slightly above human temperature. Hence, the device was stuck to the skin and when the time came to remove it, its temperature raised slightly, resulting in its easy removal. The heating mode of the device could even be carried out by the device itself wirelessly. This material was tested on various people and managed to be removed easily without any irritation. Table 8 schematically depicts the Health and Safety-related papers used in this paragraph.

Table 8. Definition of the research in the category Health and Safety (Health).

3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle

Equipment Design		Social Care Technology	
Researchers	Keyword	Researchers	Keyword
Bukauskas et al., 2021 [103]	Auxiliary tool	Olson, 2018 [114]	Sensor system
Nilasaroya et al., 2023 [104]	Auxiliary tool	Callihan et al., 2023 [115]	Sensor system
Suen et al., 2021 [105]	Auxiliary tool	Sanfilippo and Pettersen, 2015 [116]	Sensor system
Iftikhar H. and Luximon, 2021 [106]	Auxiliary tool	De Fazio et al., 2022 [117]	Sensor system
Liang et al., 2018 [107]	Auxiliary tool	Abbasianjahromi and Sohrab, 2022 [118]	Sensor system
Laffan et al., 2020 [108]	Sensor system	Xie and Wu, 2023 [119]	Sensor
Jeril and Sarath, 2019 [109]	Sensor system	Lin et al., 2022 [120]	Sensor
Zhang et al., 2021 [110]	Sensor system	Stetter et al., 2019 [121]	Sensor
Tartare et al., 2018 [111]	Sensor system	di Paolo et al., 2021 [122]	Sensor system
Park et al., 2019 [112]	Sensor system	Matijevich et al., 2019 [123]	Sensor system
Van Kleunen et al., 2019 [113]	Sensor system	Xie et al., 2019 [124]	Sensor
		Zhao et al., 2022 [125]	Triboelectric
		Gao et al., 2017 [126]	Sensor
		Picchio et al., 2022 [127]	Sensor
		Kang et al., 2022 [128]	Sensor
		He et al., 2019 [129]	Triboelectric
		Mahmud et al., 2016 [130]	Auxiliary tool
		Jinkins et al., 2022 [131]	Auxiliary tool

2.7. Smart Textiles

2.7.1. Textile Sensor

Jiang et al. [132] built a smart fabric with wireless communication and power to monitor a person's temperature and sweat. Using a conductive thread on a fabric, an NFC-type (Near Field Communication) antenna was created. The temperature and sweat sensors were connected to the NFC antenna. The overall system for monitoring the measurements was implemented using a smart phone. The smart phone used the application resistance when it was close to the NFC antenna, powered the device and took the readings of the two sensors. After several tests carried out the smart fabric appeared to meet the requirements of its design.

Zhao et al. [133] investigated a smart fabric for manufacturing a flexible piezoelectric sensor for applications in wearable products. The smart fabric comprised knitted coaxial fibers, a nylon substrate, evaporated Au layer and carbon fibers. These materials with their appropriate combination in levels and after penetrating treatments (i.e., polymerization) realized the smart fabric. When pressing on the fabric, a signal was recorded. After various tests of the manufactured sensor, it was found that its operation was excellent without problems and interference. Also, this smart fabric showed very good durability.

Maity et al. [134] built a wearable sensor using smart fabric to record movement and humidity. The smart fabric consisted of multi-layer carbon nanotubes and the use of a layer-by-layer method. In the study, research was carried out to find the appropriate structure and the optimum conditions for the conductive properties of the fabric. The device was placed on various areas of the human body (i.e., cheek, forehead, wrist, elbow, neck, knee and abdomen). Based on the resistance of the fabric, a computer could instantly record the change in sensor size as well as the humidity of the area.

García et al. [135] designed a smart fabric using an inductive sensor to monitor spinal flexion. A sensor imprinted on a textile surface was fabricated and could record the elongation of its shape. More specifically, a garment was developed in which a special seam of metal thread was made. The seam formation on the flexible fabric had a checkered pattern as it should be able to accommodate elongation. With this method, an inductive sensor was built, whose operation was based on magnetic field changes principles. In essence, the magnetic field, which was created during the flow of current from the thread, showed changes during the change of the shape of the thread (elongation of fabric, i.e., forward bending). At the end of the research, tests were carried out from which it emerged that the device could accurately record a forward bend of the body but was unable to separate it from other similar lateral bends.

Capineri [136] analyzed and described the smart fabrics of the last decade used in the manufacturing of wearable products. They also mentioned how such a fabric could relate with a sensor or even become a sensor itself. A key property of smart fabrics is their electrical conductivity as well as the resistance they carry when transporting an electrical charge. Based on this characteristic, the design of a device created from the thread with metallic elements was presented and could record data related to a person's walking. A piezoelectric sensor was made available and was able to record the pressure exerted on it in the time domain. The device could be placed inside the shoe in order to record the frequency of steps. In addition to the frequency, another characteristic of the sensor was the recording of the pressure duration of each step. Recording this data could provide various solutions when designing new wearable devices.

Fan et al. [137] investigated a smart fabric using conductive and non-conductive threads which could record a person's heartbeat and breathing signals. The Triboelectric All-Textile Sensor Array (TATSA) smart fabric was transformed into a triboelectric sensor array, based on the special knitting and the conductivities of the yarn. With each change in fabric size, the corresponding signal was recorded. Based on this feature, various applications were created such as collar sensor, wrist sensor, finger sensor, ankle sensor and upper abdomen sensor, where each of them could record the heartbeat or breathing of the person. Finally, an integrated application was presented, in which two smart fabric sensors were sewn onto a garment in the abdomen and wrist area. The integrated application could record the patient's heartbeat and breathing cycles for a long time.

Hossain et al. [138] built a wearable self-powered fabric. The smart fabric consisted of a textile piezoelectric autonomous mechanism and a self-powered sensor. The goal was to utilize the energy produced by mobile devices. The manufacturing method of the smart fabric was the sandwich structure of two fabric electrodes, fabric conductors and a Poly(vinylidene fluoride) (PVDF) piezoelectric thin film. At the end of the study, the smart fabric was able to detect breathing or record a person's steps through electrical signals. It also had the ability to store energy so that it could power devices such as calculators, timers, LEDs, etc.

2.7.2. Applications

Golparvar and Yapici [139] studied a smart fabric from office threads to control eye movement. A conductive yarn fabric sensor was developed through a coating and drying process. A headband was then created and eight sensors (pieces of the smart fabric) were attached with metal connections. With every movement of the eyes, movements were made on the forehead and were recorded by the sensors. This was followed by the design of an algorithm, which traversed all the data, sorted the signals and extracted the possible eye positions. Based on this system, an application was built in which a user controlled a grid of led lamps. The grid consists of 25 LEDs (5×5), which light up individually depending on the position of the eye.

Luo et al. [140] designed a multisensor of pressure and touch from a smart fabric with the purpose of using it in various applications. The smart fabric was highly flexible and could sense contact and pressure by measuring electrical resistance. More specifically, the fabric consisted of a two-layer knitted structure that involved the use of conventional and conductive yarns. Thanks to a special mesh, the device could record the pressure in different areas, thus making it ideal for human-machine interaction. Other possible applications of smart fabric could be its use in entertainment industry and education. As part of the study, various wearable devices were fabricated using this technology. Some of them were knitted controllers, knitted gloves (for controlling another device), knitted socks (for activity detection) as well as knitted robotic arm cover (to record its movements).

Ahmed et al. [141] has manufactured a smart fabric that could increase its temperature in a controlled and stable manner. The smart fabric was made by dipping synthetic cotton fabric in reduced graphene oxide (rGO) due to its high electrical and thermal conductivity and poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) (CGP). Applying an electrical charge to this fabric could control its temperature to rise. Following the study, two applications were created, where the heated fabric was adapted to the finger and palm of a volunteer. The temperature was able to be maintained at constant levels with constant times in repetitive reheating cycles. The smart fabric did not show different results after several repeating washings. Therefore, the heated fabric had an excellent resistance to possible external damage and thus many devices could be developed, i.e., for health care, pain relief, or sports rehabilitation.

Nanjappan et al. [142] designed a system with a wearable device for the purpose of human-device interaction, while driving a car. The wearable device, which was in the form of a glove, was made using smart fabrics combined with sensors. The glove could read a series of specific commands in order to perform a process, i.e., driver communication with the car systems. The main objective of the study was to reduce the distraction of the driver that was encountered often with the use of touch screens inside the car. The glove, which was designed around the wrist, could perceive 16 different gestures (wrist movements) to convert them into commands. The device was tested by 18 volunteers, while driving in a digital driving simulator. The results of the tests proved that the system needed more development for its successful use.

Meng et al. [143] made a smart fabric for recording signals from the human body. The smart fabric was created from polyester, nylon yarn and Ag-coated fabric. An important feature of the fabric was the great sensitivity to the low pressures it received. The two possible applications proposed in the study were heart rate monitoring as well as the diagnosis of Obstructive Sleep Apnea-Hypopnea Syndrome (OSAHS) related to breathing problems during sleep. Regarding the diagnosis of OSAHS, it could be performed with overnight monitoring.

Papachristou and Anastasiu [144] used digital clothing design software to embed antennas inside for use in various applications (health, security, sports, communication). The main objective was to maintain the fashion and aesthetic design of the garment combined with trouble-free operation of the antenna. Two basic types of antennas used, were the patch antenna (a flat device that was sewn onto the fabric) and the button antenna (a device that used the metal buttons on the garment for an antenna). Finally, four case studies were presented in which the corresponding antennas were integrated. The integration of the antennas in each case used a different method to be hidden under the clothes.

Zhuo et al. [145] investigated a hybrid e-fiber finger motion sensor. More specifically, an electronic load sensor was constructed in order to monitor the movement through its elongation and contraction. The main goal was to increase the range of motion compared to the corresponding sensors. The particular sensor was composed of flexible porous polydimethylsiloxane (PDMS) and multiwalled carbon nanotubes (MWCNTs). At the end of the study, the sensor was integrated in a smart fabric so that it could be placed on a finger. The result of the study was the complete application of the sensor on the hand as well as the recording of its movements in real time.

Xu et al. [146] built a multifunctional sensor from flexible smart fabric with the ability to breathe and create a wearable heater to monitor and treat a person's health in real time. The multi-function sensor was fabricated from carbon fiber yarn (CFY) and polyurethane (PU) fiber. A key characteristic of the sensor was its high conductivity as well as its great sensitivity in detecting movements. The sensor had the ability to record multiple human stimuli such as elbow flexion, finger movements and pulse. The wearable heater was made of conductive material and placed in a coil formation. With low power supply the portable heater could increase its temperature. The combined use of the above two smart fabrics could improve both health monitoring and the treatment of a specific disease. Table 9 schematically depicts the Smart Textiles-related papers used in this paragraph.

Table 9. Definition of the research in the category Smart Textiles (Smart).

3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle

Textile Sensor		Applications	
Researchers	Keyword	Researchers	Keyword
Jiang et al., 2020 [132]	Sensor	Golparvar and Yapici, 2019 [139]	Sensor
Zhao et al., 2020 [133]	Sensor	Luo et al., 2021 [140]	Sensor
Maity et al., 2021 [134]	Sensor	Ahmed et al., 2020 [141]	Sensor
García et al., 2020 [135]	Sensor	Nanjappan et al., 2019 [142]	Sensor
Capineri, 2014 [136]	Sensor	Meng et al., 2020 [143]	Sensor
Fan et al., 2020 [137]	Sensor	Papachristou and Anastassiu, 2022 [144]	Sensor
Hossain et al., 2022 [138]	Triboelectric	Zhuo et al., 2023 [145]	Sensor
		Xu et al., 2023 [146]	Sensor

2.8. Athletics

Kos et al. [147] presented the operation of biofeedback systems in the field of sports. Biofeedback is a process that starts from the recording of an athlete's movement data, continues with the processing of the data and results in improving the athlete's movements in a consultative manner. The categories of sensors used to record the data as well as the wireless data transmission methods were presented. Important limitations were also mentioned, in both the architecture of the systems and the processing of the data. One of the final conclusions of the study was the difficulty to find a system that could satisfy the requirements of many different application scenarios for biofeedback. Kos et al. [148] praised the new technologies entering the field of sports in order to upgrade them. In this study, a brief introduction to the integration of smart devices and systems in sports was presented. The benefits of such a move were undoubtedly many. The use of sensors could record a great deal of data and extend the capabilities of human senses. The combination of hardware with sophisticated software could create rapid machine learning. In essence, the system recorded the movements of the athlete, processed the data and finally extracted the correct instructions with an aim to improve the specific movements. It was expected that the role of the traditional coach could completely change or even be replaced as many elements of new technologies would be introduced into this role.

Zhao and Li [149] designed a portable system for monitoring the movement of an athlete with the possibility of using it during the sport. The wearable device comprised the microcontroller, the power supply unit and the data relay antenna. One or more nine-axis sensors could be connected to the controller. Each sensor included a three-axis gyroscope, a three-axis accelerometer, and a three-axis magnetometer. During the operation of the system, data filtering was performed in order to measure the angle of the body.

Wahab and Bakar [150] designed a wearable device for monitoring the movements of the foot during sports using ultrasounds. The quick prediction of a possible future injury was a very important piece of information that every athlete should be aware of. A device was created and positioned in the shoe, which, through ultrasounds, could record the kinematic movements of the foot during sports. Data were collected by a microcontroller and sent wirelessly to a host computer. The computer had the appropriate algorithm to convert the measurements into the athlete's gait pattern. By evaluating the gait pattern, the sports injury of the athlete could be avoided.

Kos and Kramberger [151] developed a wearable device for monitoring hand movement in sports activities. The system presented in the study aimed to analyze sports (i.e., tennis, golf) based mainly on hand movements. The tracking device fitted on the athlete's hand in the wrist area and had a gyroscope, an accelerometer, temperature and heart rate sensors. The data was initially recorded in a microcontroller and were transferred to a computer for better visualization of the measurements and the general performance of the game/athlete. The feature of this particular system that differentiated it from several similar devices was the simultaneous acquisition of biometric data, which in the future could perform a better analysis of the athlete's performance.

Kidman et al. [152] fabricated a wearable device with biofeedback features for training professional divers. The purpose of the device was to improve the technique combined with the reduction of fatigue in order to achieve better performances. The system's communication started with recording the diver's movements, continued with the processing and evaluation of the movements and ended with the feedback of the diver about the user's kinematic errors. This whole process took place in real time. More specifically, the device had sensors for recording movements as well as a vibration motor. The device was connected to the coach's mobile, then all data were sent in real time from the diver's device to the coach's device. The use of the vibration motor was related to the diver's feedback method, i.e., sending a message from the coach to the athlete. Each such message was associated with movements and their execution times. The operation of the device was evaluated by experiments with three divers. The results of the experiments showed that the device had accurate measurements and a short deviation time compared to a motion video. With this system, an integrated application was created that could improve the way athletes are trained both in the training stage and in the competition stage.

Li et al. [153] presented a low-cost sensor for tracking sports activities. The sensor could record pressure changes and its main construction material was cotton. Using a special treatment, the cotton together with the conductive polydimethylsiloxane (CC/PDMS) composites was turned into a pressure sensor that could register pressure from 6.04 kPa to 700 kPa. By integrating the sensor in a belt and a shoe of an athlete, a monitoring of his sports activity could be carried out. Beyond the use in the field of sports, such a device could be adapted to many future applications such as health monitoring, sports performance, wearable electronic devices and human-machine interface devices.

Ishida [154] made available a system for recording movement data during skateboarding. The aim of the research was to record and manage the movement data so as to produce various important conclusions about the evolution of the skateboard usage. The system used three sensing devices (two on the skateboard and one on the human body) in order to record the data. The data were stored and then sent to a computer for evaluation. As a part of the study, various experiments were carried out to check the system as well as to draw conclusions for improving its use. From the results of the measurements, three factors were distinguished by which the optimal speed could be achieved: the skateboard's tilt change, alternating tilt change and reverse movement between the upper and lower body.

Iervolino et al. [155] built a wearable device to monitor and evaluate the performance of a person's movements during sports activity. The device was placed above the ankle and used a three-axis accelerometer and a three-axis gyroscope to record movements. It also had barometric sensors to monitor pressure and humidity. The measurement data were stored and processed before being sent to a computer by a microcontroller. Then the data were sent wirelessly to the computer for evaluation and extraction of complex performance indicators. After several tests of the system, the algorithm was able to distinguish standing, walking, and running situations. Also, from the data collected it was easy to detect the contact time between the foot and the ground. Hsu et al. [156] built a wearable tracking system to identify sports and non-sport activities. The system consisted of two monitoring devices, the data recording and the processing software. The two devices were worn on the user's wrist and ankle and contained a microcontroller, a power supply circuit, a three-axis accelerometer, a three-axis gyroscope and a wireless transmission unit. The algorithm was able of performing signal recording, signal processing, human motion detection, signal correction and activity recognition. As part of the study, tests were carried out with 23 volunteers and 21 activities (10 daily activities and 11 sports activities). The algorithms succeeded in achieving recognition rates of 98.23% for daily activities and 99.55% for sports activities.

Huang et al. [157] designed a self-powered sensor to monitor sweat during exercise. The device had the ability to be charged using human sweat. More specifically, the device consisted of absorbent paper (immersed in an aqueous solution of graphene), a thin layer of magnesium and a thin layer of cotton containing potassium chloride (KCl) powders. By introducing sweat inside the device, a reaction took place between the metals, which in this case were the electrodes of the system. The reaction between the metals and the sweat caused a transfer of electrons, resulting in the production of electricity. In addition to energy-producing components, the device had a sensor to analyze and monitor the sweat as well as a Near-Field Communication (NFC) antenna for sending the data to a smart phone. Sweat analysis included the measurement of Na+ concentration, pH value and skin resistance to prevent dehydration.

Xuan et al. [158] prototyped a device worn by athletes to collect lactate sweat for the purpose of on-site perspiration analysis. The device was placed on the skin during sports such as cycling and kayaking. The design of the device helped to collect sweat while processing was carried out through a validated biosensor. The whole process was completed using a custom application that processed the data in real time.

Burland et al. [159] tested and evaluated a sports tracking sensor with real conditions of use by a soccer player. Various tests of the Blue Trident Inertial Measurement Unit (IMU) sensor were performed in this study. The tests were divided into three time periods with an intermediate rest of the athlete of 7 to 10 days. At each stage, ten healthy soccer players repeated a series of four specific exercises. The four exercises were acceleration and deceleration in a straight line, acceleration and diagonal turn, acceleration and return, and finally kicking a soccer ball. From the results of the device measurements, it emerged that there was a high repeatability between the same athletes in all stages in which the same exercises were repeated. Therefore, portable sensors of this category could be considered reliable as far as the recording of measurements was concerned.

Castillo-Atoche et al. [160] built a self-powered and wearable system to detect a person's cardiac arrhythmia during exercise. The system consisted of a heart rate monitor (on the chest area), a small photovoltaic circuit with battery (the arm area) and data management software. The system was able to record heart beats during sports training and categorize them into normal and abnormal beats. Categorization was achieved with a Convolutional Neural Network (CNN) algorithm. After several tests, it emerged that the system could accurately categorize heartbeats between the two categories. Also, the use of photovoltaic increased the function of the device so that it could be used for a longer period of time without manual charging.

Hsu et al. [161] implemented a system for monitoring and recognizing sports activities. The system consisted of two monitoring devices and an algorithm for processing and categorizing the data. The two devices were worn on the athlete's wrist and ankle and included two sensors (a triaxial accelerometer and a triaxial gyroscope). Also, the devices used a power supply unit, a microcontroller and the wireless radio frequency (RF) transmission unit. The system was then tested by 10 athletes who performed various sports activities. Finally, an algorithm was designed for managing the data and categorize the movements of the athletes based on 10 sports activities. Specifically, the algorithm used a deep convolutional neural network (CNN) to recognize the activity performed, based on motion spectrograms. Finally, the percentages of successful operation of the system were compared with three corresponding systems. From the result of the comparisons, it was shown that the tracking system created had improved results compared to the other three methods.

Zhou et al. [162] established a wearable sensor system for monitoring muscle activities during exercise in a gym. The device consisted of a complex multi-sensor that was wrapped like plastic around the leg in the area of the quadriceps. The sensor was flexible and used an 8×16 grid to record 128 pressure points. Using various tests of the system on six participants, the movement recognition accuracy was calculated to be 81.7% on average. As a result, the device could be used to identify a sports activity as well as to evaluate its quality. Future developments of the system include the use of a battery and the wireless transmission of data with an aim to increase its portability.

Umek and Kos [163] designed a wearable device for recording important data in marine sports. In water sports, the timing of various events plays a decisive role in the athlete's performance. In this research, a waterproof device was created that contains a 3D accelerometer and a 3D gyroscope inside. Recording the data of movement and position in relation to time could help a lot in improving the athlete's performance through his/her guidance. Three possible application scenarios of the mobile device were presented in the research, i.e., swimming, canoeing and kayaking. As a result, an overall monitoring of many water sports could be achieved.

Hurban [164] researched already existing wearable technologies in order to create a tracking device embedded in a garment. The wearable device had the ability to record the movements of the body as well as emit various sounds corresponding to the movement. As part of the research, traditional dances from Spain and Turkey were investigated. More specifically, their names were "Flamenco" and "Mevlevi". Various applications of wearable products were also presented, where each one provided a function of its own. The main objective of the research was to search for common elements of the music and dance of two different cultural heritages through the use of a modernized traditional costume (dance outfit with an integrated wearable device).

Cannavò et al. [165] presented a portable system for sports training using Virtual Reality (VR) technology. More specifically, a VR platform was developed for the purpose of analyzing and training the athlete's movements during sports. The device using biofeedback could inform the user in order to improve a technical gesture. For this purpose, a reference movement originating from the user himself was used. In this way, a comparison of subsequent movements with the reference movement was made. The reference move was replaced with each new better move. The use of VR technology could provide a virtual environment in which one can see the space from different angles. In the end, the system was tested by 18 non-specialized volunteers. In the experimental tests, the volunteers were evaluated in the sport of basketball and more specifically in the free throw. Based on the results, it appeared that the application of this system could improve the athlete's gestures both temporally and spatially.

Jenkins and Weerasekera developed a portable device for checking the correct body posture while performing weight lifting exercises. The wearable device was worn at the back of the athlete's body so that it can keep track of the spinal inclination during the exercise. The device consisted of separate sensor nodes that could record the inclination of the spine at the respective placement points. The aim was to avoid the inappropriate posture of the body when lifting the weight, a fact often observed by teenagers and novice athletes. The spine must remain in a straight line throughout the movement. Device data was recorded and provided feedback on posture correctness in real time. At the end, the device was tested with four athletes. From the test results it was concluded that the spine correctness check could be performed even with only two sensor nodes [166]. Table 10 schematically depicts the Athletics-related papers used in this paragraph.

Table 10. Definition of the research in the category Athletics (Athle).

3D P	**Anthro**	**Co De**	**Kine**	**Foot**	**Health**	**Smart**	**Athle**

Part 1/2		Part 2/2	
Researchers	Keyword	Researchers	Keyword
Kos et al., 2019 [147]	Sensor system	Huang et al., 2022 [157]	Sensor
Kos et al., 2018 [148]	Sensor system	Xuan et al., 2023 [158]	Sensor
Zhao and Li, 2020 [149]	Sensor system	Burland et al., 2021 [159]	Sensor
Wahab and Bakar, 2011 [150]	Sensor	Castillo-Atoche et al., 2022 [160]	Sensor system
Kos and Kramberger, 2017 [151]	Sensor	Hsu et al., 2019 [161]	Sensor system
Kidman et al., 2016 [152]	Sensor	Zhou et al., 2016 [162]	Sensor system
Li et al., 2015 [153]	Sensor	Umek and Kos, 2018 [163]	Sensor system
Ishida, 2019 [154]	Sensor	Hurban, 2021 [164]	Sensor system
Iervolino et al., 2017 [155]	Sensor	Cannavò et al., 2018 [165]	Robotic technology
Hsu et al., 2018 [156]	Sensor	Jenkins and Weerasekera, 2022 [166]	Auxiliary tool

3. Summary of Key Research Areas Depicted

The first category of studies that emerged from the review was related to the use of 3D printing in the design of wearable products. This category consisted of 19 research papers and was divided into two sub-categories: Aesthetics and Technology with eight and 11 research papers, respectively. A common feature identified in the first subcategory was the need for flexibility in the final product. The elasticity of the printed geometries achieved by using links or flexible materials was a key factor in the fabrication of various garments. On the other hand, in many cases the integration of sensors in the printed geometry was observed. The use of these sensors could turn the product into a monitoring device, where collected data could be evaluated at a later stage.

The second category of research works discovered from the review was related to the anthropometric design of wearable products. This category consisted of 24 research papers and was divided into two sub-categories: Prototyping and Measurement with 14 and 10 research papers, respectively. In the Prototyping subcategory, the main purpose was the creation of both custom and unisized products. The use of digital tools such as 3D scanning and 3D printing was carried out in most of the research work. Through digital tools, the design of products could be improved to a great extent, as a result of which, each product could be fitted dimensionally with the corresponding user. In the second subcategory, the main purpose was to collect and evaluate data from many people in order to categorize their main dimensions. And in this case, the use of 3D scanning was necessary in order to record all the required measurements.

The third category of research works emerged was related to the use of computational design in the development of wearable products. This category consists of 21 research works and was divided into two sub-categories, namely Design Advancements and Health-Based Applications, which have 14 and seven research works, respectively. Product development using algorithms was a key feature of the first subcategory. It was based on methods of geometries parametric design. Three-dimensional scanning was a common method for collecting anthropometric data, which was the input data of the algorithms. In this subcategory, each algorithm processed the data passed by the users and produced a product that suited the respective user. On the other hand, in the second sub-category, the studies collected were aimed at the health of the users. In many cases, devices were created through algorithms aimed at rehabilitating users after injury. It was important to mention that the fabrication of orthoses using 3D printing was the most common restoration method.

The fourth category of research works depicted from the review was related to the design and development of applications based on the kinematics of the human body and contained 19 research papers. In this category, the anthropometric characteristics of users were studied in order to create exoskeletons. In most cases, it was necessary to measure movement and joint area. The designed exoskeletons, aimed at rehabilitating patients, assisting users and remotely controlling humanoid robots. In essence, exoskeletons were divided into two types: exoskeletons with active movements and exoskeletons with passive movements. The difference between these two types was that in the first case, the exoskeleton caused the movements of the user, while in the second case the user caused the movements in the exoskeleton, which had the ability to record them.

The fifth category of studies emerged was related to the design of products worn on the feet of users and contained 16 research papers. A key feature of this category was the presence of pressure sensors. In many cases, the need to record plantar pressure was observed. The data collected by the sensors were the basis on which the studies were performed. It is important to mention that in many studies, energy production devices were designed through a triboelectric nanogenerator. It was a method of producing energy through pressure, which in this particular case was carried out from the sole during walking or running. In essence, the weight of the body could produce an electric current, which charged an electric power device.

The sixth category of studies depicted from the review was related to the development of portable products for the health and safety of users. This category consisted of 29 research papers and was divided into two sub-categories: Equipment Design and Social Care Technology with 18 and 11 research papers, respectively. In the first subcategory, products were developed with an aim to ensure the health of users. More specifically, there were smart products that helped professionals, performing their activities in a safer manner. For example, uniforms with integrated monitoring and feedback devices were designed for firefighters to check their safety. On the other hand, in the second subcategory, studies related to the development of integrated health monitoring systems were collected. Various sensors were developed and used in this subclass to monitor multiple human vital signs.

The seventh category of research work depicted from the review was related to the fabrication of smart textiles for the development of wearable products. This category consisted of 15 research works and was divided into two sub-categories: Textile Sensor and Applications with seven and eight research papers, respectively. In the first category, most of the research focused on the implementation of new sensors. The new sensors were made of smart fabrics, making them flexible and wearable on the human body. In recent years, the use of 3D printers for creating smart textiles has increased. In the second subcategory, the studies collected were related to the creation of integrated applications. These applications used sensors and smart fabrics to track movements and remotely control devices. In many cases, the sensors were created by the smart fabrics themselves.

The eighth category of research works was related to the design of wearable sports products and contained 20 research papers. In this category, devices and systems were developed to monitor the movements of athletes. These devices had the ability to be worn on the human body during exercise. The use of sensors such as gyroscope and accelerometer were very common in most studies. Also, a part of the research dealt with the feedback of the athletes in order to improve the performance of each exercise. In this way, a wearable device could take on the role of a personal trainer by having movement data, that a normal trainer would not have. In many cases, extensive use of sensors with an aim to record vital signs, such as heartbeats during exercise, was implemented.

Figure 3 provides a pictorial view of the research categories used in the current research review. In some of them, subcategories were not proposed, while in others more were used with an aim to describe the review outcome with increased accuracy. At the same time, the size of each named area provides extra pieces of information about the number of the papers that were depicted and analyzed.

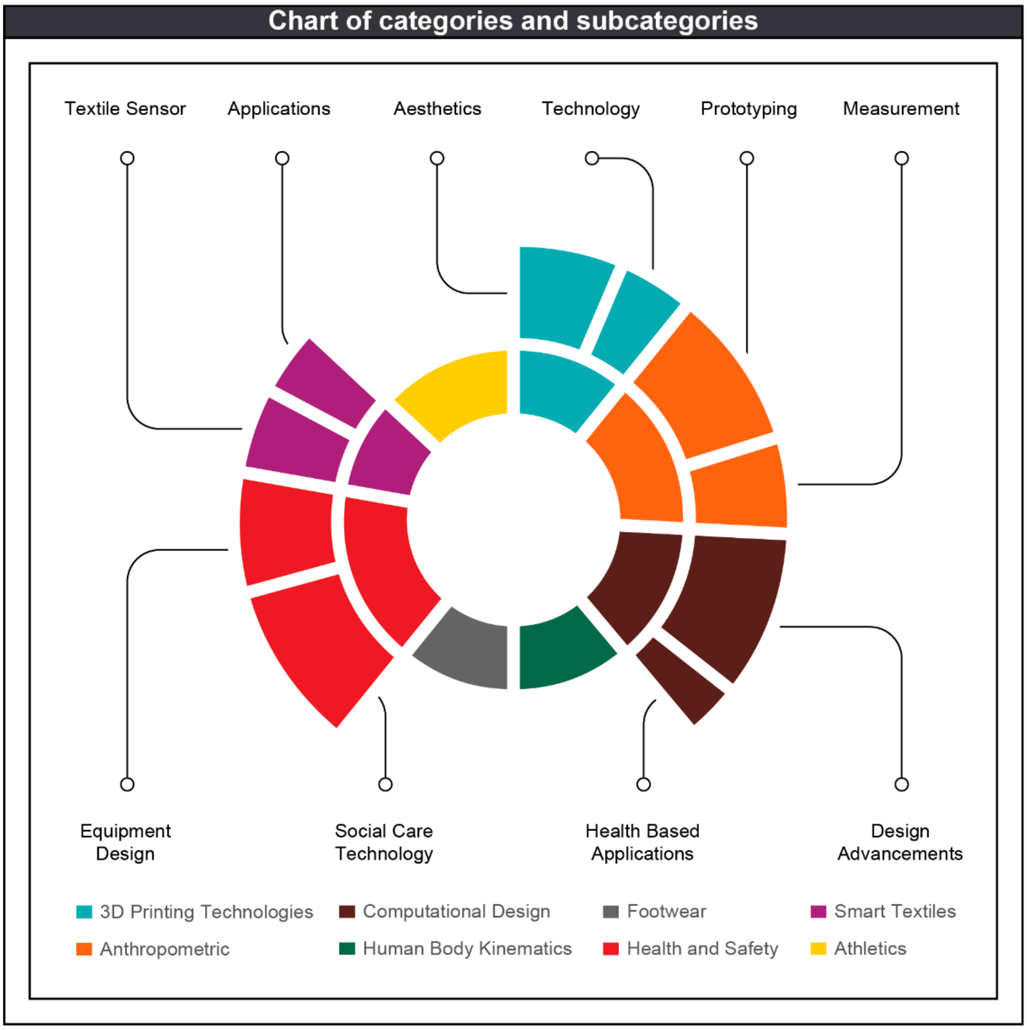

Figure 3. Categories and subcategories depicted from the review process.

Figure 4 provides information about the publication year of the papers used in the current research review. These papers were separated based on the categories proposed. It was evident that there was a substantial increase in studies in the areas of 3D Printing Technologies, Computational Design and Health and Safety. Nevertheless, in the time period between the years 2020 and 2021, there was a reduction in the research work related to Anthropometrics, Human Body Kinematics, Footwear, Health and Safety, Smart Textiles and Athletics. Overall, an effort was made to emphasize the collection of studies published in the last six years in order to be able to recognize the research trends and research gaps.

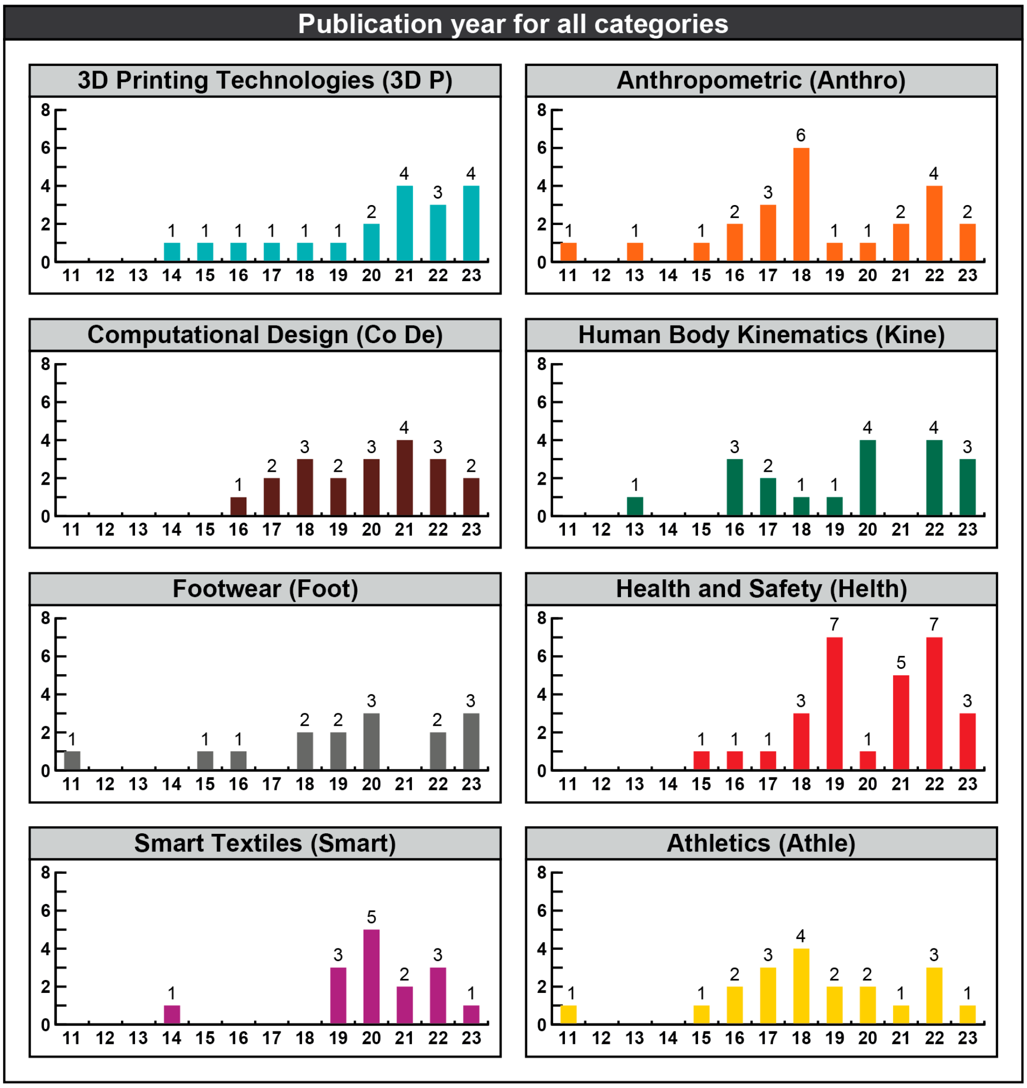

Figure 4. The distribution of research papers selected in the current review with respect to the publication year and the category included.

At the end of each category depicted previously, a table was presented (Tables 3–10) which contains not only the research papers included in each category but an additional keyword related to the published research. The aim of these keywords' definition was to connect each research paper with a single word/phrase, which could capture in a simple way the objective and thematic included. Table 11 provides an overview of the categories used in the present review research work and associates them with the series of keywords depicted previously. A series of conclusions could be used as outcomes about the direction that the researchers follow:

- The phrase Auxiliary tool was associated with a number of categories presented, i.e., Anthropometric (Anthro), Human Body Kinematics (Kine) and Health and Safety (Health).
- Body measurement was mainly included in Anthropometric (Anthro) and Computational Design (Co De) areas.
- Robotic technology was linked with the Human Body Kinematics (Kine) research area.
- Sensors were very popular in most of the categories depicted, i.e., 3D Printing (3D P), Anthropometric (Anthro), Health and Safety (Health) and especially in Smart Textiles (Smart) and Athletics (Athle).
- Sensor systems received recognition when applied to Footwear (Foot), Health and Safety (Health) and Athletics (Athle).

Table 11. The connection of the categories with the keywords that emerged.

Key Words	3D P	Anthro	Co De	Kine	Foot	Health	Smart	Athle
3D pattern	1		1		1			
3D/4D printing	5	1	3					
Auxiliary tool	2	5	7	11		7		1
Body measurement		7	6					
Measurement optimization	1	4			1			
Metamaterial	1				1			
Parametric design	1		4					
Robotic technology		1		7				1
Sensor	6	5				7	14	10
Sensor system		1		1	11	13		8
Triboelectric	2				2	2	1	

In addition, there were more outcomes about possible research gaps that need extra attention in the future, such as:

- More emphasis could be given in using 3D pattern and 3D/4D printing in all the categories studied.
- The categories: Human Body Kinematics (Kine), Footwear (Foot), Health and Safety (Health), Smart Textiles (Smart) and Athletics (Athle) presented low connectivity with the keywords: body measurement, measurement optimization, metamaterial and parametric design.
- Research opportunities could be related in connecting Computational Design (Co De) with a series of keywords, i.e., measurement optimization, metamaterial, robotic technology, sensor, sensor system and triboelectric.

Figure 5 presents additional opportunities for guiding future research based on a new set of associated words among all the presented categories. A set of three words emerged from performing the present review: product (P), measurement (M) and sensor (S). On the left-hand side graph, the correlation of each category (product/measurement/sensor-oriented) with the rest of them is presented, i.e., Anthropometric (Anthro) is connected via the product (P) with 3D Printing Technologies and measurement (M) with both the Health and Safety (Health) and Human Body Kinematics (Kine).

When restructuring the network of associated words, the right-hand side graph provides an additional set of outcomes:

- 3D Printing Technologies (3D P) are strongly associated with Computational Design (Co De), Smart Textiles (Smart) and Anthropometric (Anthro) via the design of products (P).
- Health and Safety (Health) is strongly associated with measurements (M) related to Antropometric (Anthro) and Human Body Kinematics (Kine).
- Health and Safety (Health) has strong links with Smart Textiles (Smart), Footwear (Foot) and Athletics (Athle) via the use of sensors (S).

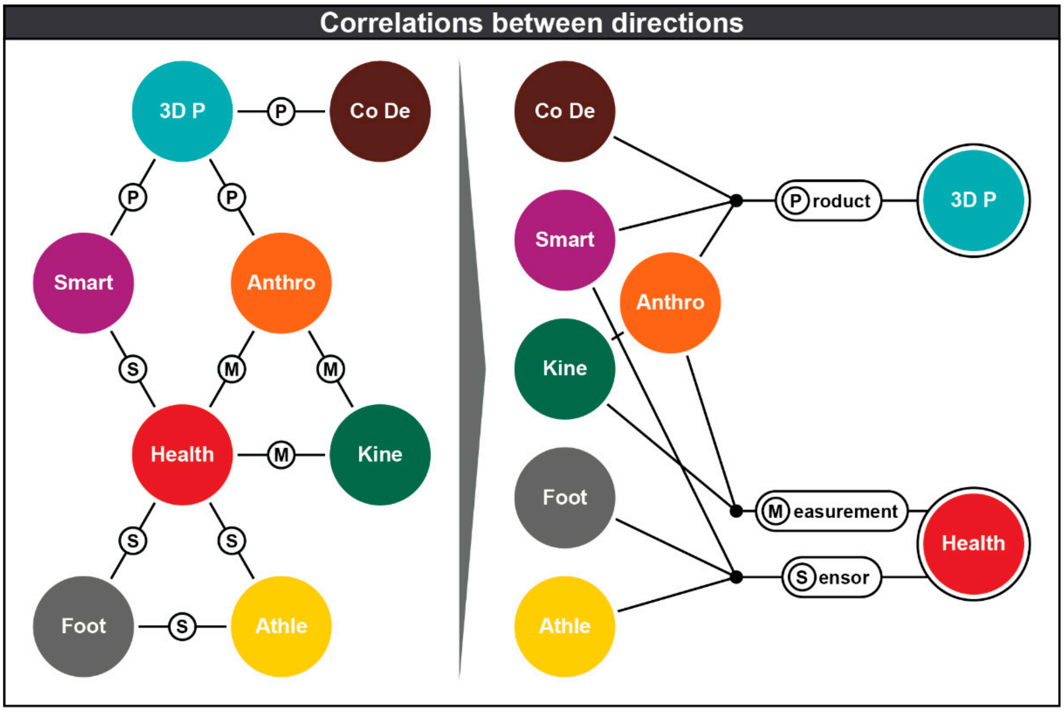

Figure 5. The research categories associated with product (P), measurement (M) and sensor (S).

4. Conclusions

In this study, a review was carried out in the design and fabrication of wearable products. The use of wearable products is a trend that has been growing significantly in recent years. The use of new technologies is one of the main factors responsible for this increase. Tools such as 3D scanning and 3D printing facilitate the appropriate processes and significantly reduce their costs, making it a straightforward approach in many cases. It is important to mention that parametric and computational design are two design technological tools that come to fill a substantial gap in custom product design.

According to the present review, the majority of the collected studies had a direct or indirect purpose for the safety and health of people. In many cases, products/devices/systems were developed for the prevention and health monitoring as well as for rehabilitation after injury. It is true that the integration of various micro-sensors was used in a large number of studies. The design and fabrication of every new sensor within the wearables can be improved as well as to create new products.

The review presented a great deal of details about the research papers used (161) as the basis for collecting more pieces of information about (a) the current research trends followed and (b) discovering research gaps that can lead to increase work towards new directions. As a result, eight main categories emerged: 3D Printing Technologies (3D P), Anthropometric (Anthro), Computational Design (Co De), Human Body Kinematics (Kine), Footwear (Foot), Health and Safety (Health), Smart Textiles (Smart) and Athletics (Athle). Beyond the common feature of wearable product design, these research directions are connected through three significant terms: product (P), measurement (M) and sensor (S). Three-dimensional (3D) Printing Technologies and Health and Safety were the two main categories connected to most of the directions provided, thus proving their importance. It is expected that the wearables industry will grow fast and will expand towards a variety of everyday life applications, i.e., hospital-based services, fire extinguishing services, workforce conditions improvements, health and wellbeing, sports and everyday activities.

As future work, the authors of the current paper expect to use a series of computational product design technologies for automating the customer-dedicated product design process. Modern CAD systems will be programmed in order to automatically design customized products for the users, while making use of reverse engineering anthropometric data

(3D scanning of users' body and members). Capitalizing on the low cost of 3D printing equipment will be an additional added value to product fabrication. Further to the general-purpose materials used nowadays, using light composite materials and studying the optimized manufacturing parameters will be an additional asset. These will expand the opportunities for customized products produced in decreased time to market with low-cost fabrication and optimized metamaterials.

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