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Review on Smart Electro-Clothing Systems (SeCSs)

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Abstract

This paper presents an overview of the smart electro-clothing systems (SeCSs) targeted at health monitoring, sports benefits, fitness tracking, and social activities. Technical features of the available SeCSs, covering both textile and electronic components, are thoroughly discussed and their applications in the industry and research purposes have been highlighted. In addition, it also presents the developments in the associated areas of wearable sensor systems and textile-based dry sensors. As it became evident during the literature research, such a review on SeCSs covering all relevant issues has not been presented before. This paper will be particularly helpful for new generation researchers investigating the design, development, function and comforts of the sensor integrated clothing materials.

Key Words: Smart garments, e-textiles, biosignals, sensors, dry electrode, signal-to-noise ratio (SNR), Internet-of-Things (IoT), knitted fabrics

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1.0 Introduction

Thanks to the advancement of technology in producing microelectromechanical systems (MEMS), wearable electronics have become very common consumables on the market nowadays. Wrist-worn wearable devices (smart watches and fitness trackers) experienced a growth of 18% and 7% in the UK during the period of 2016-2017 and 2017-2018 respectively [1]. With the advent of conductive threads, textile structures either woven or knitted from conductive yarns, conductive print-inks including those from graphene, it is now possible to produce or integrate light-weight sensors onto textiles to monitor health, fitness and performance in non-clinical environment, in daily-life and in sport-training conditions [2-5]. An overview of the recent developments in wearable sensors for remote health monitoring is presented by Majumder et al. [6]; while the smart sensors and fusion systems for sports and biomedical applications are reviewed by Mendes Jr. et al. [7]. In some cases, smart sensors are worn directly on the body using belts, straps and adhesives; and in some cases, they are integrated or pocketed within textiles. The concept of Wearable 2.0 [48] envisaged full integration of wearable electronics within clothing as presented in the figure 1. A good number of smart electro-clothing systems (SeCSs) has emerged onto the market. This paper reviews the available SeCSs and the state-of-the-art development in the associated technologies such as wearable sensor-systems, and textiles based sensors. As far as it is known by the authors, such a review on SeCSs covering all relevant issues has not been presented before.

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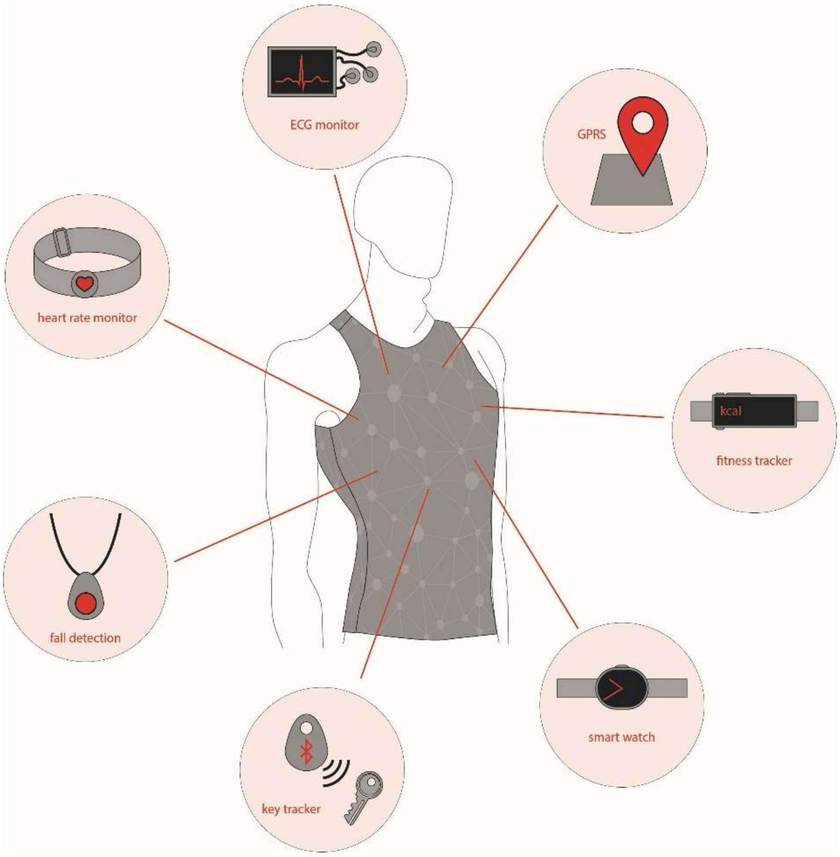

Figure 1. Concept of Wearable 2.0

To understand the rationale for integration of wearable sensors into clothing, it is important first to understand the biosignals that come from the human body. Section 2 gives an overview of the variety of biomedical signals and their classification and origins. Section 3 discusses the available SeCSs and their technical features. Sections 4 and 5 give an overview of the developments in wearable sensors systems and textile based dry sensors respectively.

2.0 Biosignals

The electrical, chemical and mechanical activities that take place in human body during any biological event such as beating of heart and contraction of muscles produce different biomedical or biosignals [8]. Based on the physiological origins of these signals, they can be grouped as bioelectrical, biomagnetic, biochemical, biomechanical, bioacoustics, bio-optical and biothermal signals (see Table 1). Bioelectric signals are generated by nerve and muscle cells because of electrochemical changes within the cells. Established processes of presenting bioelectric signals are electrocardiogram (ECG), electrogastrogram (EGG), electroencephalogram (EEG) and electromyogram (EMG). An ECG represents the electrocardiographic signal that comes from electrical excitation of heart muscle. An

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EGG captures the electric signals that travel through the stomach muscles and control the muscles' contractions. An EEG reflects the electrical activity of neurons and brains and an EMG records the electrical activity of muscles from elsewhere of the body. Biomagnetism in human organs is associated with bioelectricity existences in cells; however, the magnetic signals are much weaker than corresponding physiological bioelectric signals. Biomagnetic signals are presented as magnetoencephalogram (MEG) of brain, magnetoneurogram (MNG) of peripheral nerves, magnetogastrogram (MGG) of grastointestinal tract and magnetocardiogram (MCG) of the heart. Biochemical signals are mainly information about changes in concentration of various chemical agents in the body. Biomechanical signals are produced by different mechanical functions of the body organs, including motion, displacement, tension, force, pressure and flow. For example, blood pressure (BP) is a measurement of force that blood exerts against the walls of blood vessels and mechano-respirogram (MRG) shows respiratory cycle from changes in abdominal circumference. Sound produced by internal organs, joints and muscles are considered as acoustic biosignals that can propagate through biological medium and can be measured at the skin surface by using acoustic transducers such as microphones and accelerometers, for example phonocardiogram (PCG). Bio-optical signals are produced from optical or light induced attributes of body system. For example, optoplethysmogram (OPG) shows cardiac pulsation. Biothermal signals are output of heat loss and absorption mechanisms in the body.

Table 1: Different biosignals from human body

#	**Biosignals**	**Examples of capturing Techniques**
1	Bioelectrical	ECG, EGG, EEG, EMG
2	biomagnetic	MNG, MEG, MGG, MCG
3	biochemical	analysis of glucose, lactate, metabolites etc.
4	biomechanical	BP, MRG
5	bioacoustics	PCG
6	bio-optical	OPG
7	bio-thermal	Surface temperature

All of the above-mentioned biosignals can be further classified based on their nature of existence, i.e. permanent or induced biosignals [9]. Permanent signals exist at all time within the body and are generated without any artificial trigger, impact or excitation from outside of the body, for example, ECG and PCG signals. Induced biosignals are artificially triggered, excited or induced and they exist roughly for the duration of the excitation, for example Electroretinogram (ERG). Biomedical sensors that sense biosignals or biopotentials can be categorised as physical, electrical or chemical depending on their specific applications [8]. Different kinds of specialised electrodes are used for capturing biosignals. These electrodes could be either non-invasive (skin surface) or invasive (e.g. microelectrodes or wire electrodes). Adding electrodes and sensor on to textiles and garments is an non-evasive way of capturing and measuring biosignals.

3.0 Available SeCSs

Table 2 provides a list of SeCSs that are being offered on the market or in the offing. Based on their areas of application, they can be classified into the following four groups:

1) SeCS for health
2) SeCS for sports
3) SeCS for fitness
4) SeCS for social

Smart clothing systems that can measure biosignals, for example ECG, body temperature etc, and can be used for detecting and monitoring medical conditions, and can support recovery and rehabilitation; and those are promoted by their suppliers for medical applications are identified as SeCSs for health in this paper. The systems, which are promoted by their suppliers for sport applications including monitoring players' and athletes' physical conditions and performance, and help players/athletes and their coaches in training and coaching are considered as SeCSs for sports. The systems that help general consumers with their daily fitness activities, such as walking, jogging, running, yoga and physical exercises are reported as SeCSs for fitness in this review. The systems, which do not fall in any of the above-mentioned categories but facilitate users' social activities such as communication, entertainments and leisure activities, are identified as SeCSs for social.

Table 2: List of SeCSs available on the market

#	Type	Base Product	Supplier	Origin	Price	Ref.
1	Health Monitors	T-shirt & Vest for adults, children and babies,	Biodevices SA	Portugal	€ 650~750 (excl. software)	[10]
2		Shirt (Men's, Women and Junior's)	Hexoskin	Canada	US$ 499	[11]
3		Shirt (Men's & Women's), Bra	OM Signal	Canada	-	[12]
4		Vest, sport T-Shirt, Bra & sport Bra	Emglare	USA	US$ 199	[13]
5		Vest	Healthwatch	Israel	-	[14]
6		Socks	Siren	USA	US$19.95/month	[15]
7		Baby hat	Neopanda	USA	US$75	[16, 30]
8		Baby kimonos	Mimo	USA	US$199	[17, 31]
9		T-shirt	AiQ	Taiwan	NTD 2,980	[18]
10		Underwear	Myant	Canada	-	[19]
11		t-shirt, vest, or bra	Smartlife	UK	-	[20]
12		Shirt and cap	BioSerenity	France	-	[86]
13	Sports Training Aid	Shirt (Men's) Shorts (Men's), Leggings (Women's)	Athos	USA	Men's Shirt US$398, Leggings US$348	[21]
14		Compression T-shirt, Sports Bra, loose fit shirt (Men's & Women's)	Medtronic	USA	T-shirt US$199 Sport Bra US$155 Loose fit shirt US$173 (excl. e-module)	[22]
15		Sleeveless T-shirt	Polar Team Pro	Finland	-	[23]
16		Compression Sleeve	Komodotec	USA	US$144.95	[24]
17	Sports Training Aid& Fitness Tracker	T-shirt, Vest, Sports Bra, Socks with anklet	Sensoria	USA	T-shirt, Vest US$129~139, Bra US$119, Socks +anklet US$199	[25]
18	Fitness Tracker	Yoga Pant	Wearable X	USA	US$250	[26]
19		Sport Bra	Supa	USA	US$100	[27]
20		T-shirt	Broadcastwear	India	US$45	[28]
21	Communication, Entertainment and Leisure	Jacket	Levi & Google	USA	US$350	[29]
22		Outerwear and underwear	Spinali Design	France	US$150~500	[32]

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3.1 SeCS for health

Twelve companies have been identified as the suppliers of SeCSs that can capture biosignals from human body and their proprietary software systems can analyse those signals to report the well-being of the wearers. Tables 3 & 4 summarise the features of these products and the following subsections discuss them briefly. Out of these companies, as can be seen in the table 3, OMsignal, Myant and Smartlife are offering technology rather than any readymade product to the consumers directly. The common features of the SeCSs of this category are the use of knitted fabrics as the base clothing material upon which the electronic components are attached and integrated. The products from Neopanda and Mimo are focused dedicatedly to new-borns and babies; rest are for grown up consumers.

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Table 3: Features of the textile components (TCs) of available SeCSs for health monitoring

#	Product/Supplier	Textile Components (TCs)				Ref.
		Type	**Key Design features**	**Fabric Structure**	**Other features**	
1	Biodevices SA,	Vest	Sleeveless	Knitted (80% Polyamide, 20% elastane)	Disposable electrode	[10]
		T-shirt & baby bodysuit	Short sleeve			
2	Hexoskin	Vest	Sleeveless	Knitted (73% micro polyamide, 27% elastane)	Anti-bacterial, UV protective, quick dry fabric	[11]
3	OM Signal	Shirt, Camisole	Short/long sleeve, sleeveless	Knitted (blend of soft fibres)	Breathable and moisture management fabric, printed ECG sensor	[12]
		Bra	adjustable straps, removable and breathable padding, soft inner mesh, shock-absorbing racerback			
4	Emglare	Vest, T-Shirt,	Sleeveless and short sleeve	Knitted (100% recycled polyester)	Built-in heart rate monitor, ECG sensor, rechargeable lithium-ion battery, blue tooth antenna	[13]
		Bra & sport Bra	regular			
5	Healthwatch	Vest	Seamless knitting, front zipper. Sleeveless	knitted	Dry textile- electrodes, machine washable, with at least 50 washing cycles	[14]
6	Siren	Socks	Seamless knitting from yarn with embedded sensor.	knitted	Machine washable and dry-able.	[15]
7	Neopenda	Baby hat	e-module attached to Knitted hat	knitted	medical grade polymer and silicone	[30]
8	Mimo	Baby kimonos	baby onesie with two green stripes, a dock for the turtle module and snap button closure	Knitted (single jersey, cotton)	detachable e-module, washable	[17]
9	AiQ Bioman+	T-shirt,	available as vest, shirt or sports bra	knitted	conductive fibre-based textile electrodes, from stainless steel fibres	[18]
10	Myant Inc.	Underwear	underwear bottoms for both male and female, and sports bra	knitted	sensors “knitted” into textiles	[19]
11	Smartlife	t-shirt, vest and bra	e-module attached at the front centre near under chest area	knitted	detachable e-module	[20]
12	BioSerenity	Shirt and cap	Balaclava style knitted cap with integrated electrodes. Close-fitting short-sleeve t-shirt with sewn channels from conductive yarn	knitted	detachable e-module for cap and t-shirt, washable	[85, 86, 90,91]

Table 4: Features of the electronics modules of available SeCSs for health monitoring

#	Supplier	E-Module					Sensing Parameters	Battery			Power need (mA)	Ref.
		Weight (g)	**Dimension (mm)**	**Data transfer**	**Assembly with TC**	**Compatible App/Software**		**Type**	**Life (hr)**	**Charging**		
1	Biodevic es SA,	50	66x38x 16	Blue-tooth	Plug inside shirt pocket	VJ holter pro, Vitaljaket Telemetry	HR, HRV, ECG, movement	Li-ion 3/7 V	-	USB	1050	[10]
2	Hexoskin	40	13x42x 72	Bluetooth	Plug inside vest pocket	Hexoskin, Hexoskin X, Apple Health App, Wear OS, MapMyRun, Runkeeper, Runtastic.	HR, HRV, HR recovery (HR2), Breathing rate, Step count, cadence, stride Activity level, calories burned, sleep assessment	Li-ion 3.7 V	30+	USB	520	[11]
3	OM Signal	-	-	Bluetooth	Outer surface, on under chest	myHeart	ECG, Respiration, physical activity	-	50	-	-	[12]
4	Emglare	-	-	Bluetooth	Integrated into clothing inside	Emglare Heart, Apple Heart, google Fit	Heart Rate, ECG	Li-ion	16	wireless	-	[13]
5	Healthwatch	-	Relatively big	Wi-Fi, 3G, 4G	On outer surface above side left waist	Master caution	ECG, heart rate detection, skin temperature, respiratory, and body posture	-	-	-	-	[14]
6	Siren	-	-	Bluetooth	Above ankle	Siren App	Temperature	-	-	No charge	-	[15]
7	Neopanda	150	10x51x 19	wireless	around head	customised software	pulse, respiratory rate, peripheral blood oxygen saturation, temperature	Li-ion 3.7 V	200	-	400	[16]
8	Mimo	-	-	Bluetooth to lillipad, Wi-Fi to app	left side of stomach area	Mimo Monitor	respiration, skin temperature, body position, activity level	Li-ion	120	USB	-	[17]
9	AiQ	-	slightly bigger than a thumb	Bluetooth	snaps onto garment, over left chest	-	heart rate, respiration rate, skin temperature	Li-ion	-	-	-	[18]
10	Myant Inc.	-	45x25	Bluetooth	slides into waistband	SKIIN	heart rate, temperature, pressure, motion, body fat and hydration levels	-	48	USB	-	[19]
11	Smartlife	-	-	Bluetooth	placed in pocket of garment	-	heart rate, respiration, GPS, ECG and sEMG	-	-	-		[20]

12	BioSerenity	-		Bluetooth	Attached on top of head of cap and on the shoulders of t-shirt	Neuronaute app	EEG, EMG, ECG & respiration rate and 9-axis accelerometer	-	-	-	-	[85,86, 90,91]

a) *Vital Jacket from Biodevices*

Vital Jacket or VJ® system from Biodevices S.A. (Portugal) is claimed to be the first SeCS certified as medical device by EU's medical device directives (MDD) – 93/42/EEC [33] for collecting ECG data [10]. Its hardware system consists of a t-shirt or a vest as a carrier of conductive pathway (covered electric wire), digital recorder, SD card, battery charger and disposable electrode. For capturing biosignals, one or more electrodes need to be first placed on the recommended areas of wearer's body and the t-shirt is then donned to facilitate the electrodes to be connected with its cables. The recording device is connected inside of a pocket located at the level of side-waist. The system allows to collect ECG data from a wearer using commercial wet-electrodes for long period of time, transmits remotely, and stores all data for posterior analysis. It can measure patient's movement using a 3-axis accelerometer. VitalJacket is available in two versions (with 1 or 5 leads) for babies, children and adults and both can perform an ambulatory ECG. It has an analysis software specific for rhythm alterations, which can only be read by a health professional. Experimental applications of VJ includes stress detection in bus drivers [34] and firefighters [35] through analysis of ECG data and Heart rate variability (HRV), identification of physiological responses to stress in musicians [36] through monitoring heart rate as beats per minute (bpm) and studying stress and fatigue of first responders through ECG and continuous blood pressure monitoring in laboratory condition [37].

b) *Hexoskin*

Hexoskin from Montreal, Canada is a wearable health monitoring system that includes ECG electrodes integrated into clothing and an e-module including breathing and movement sensors [11]. The system can measure heart rate (HR), heart rate variability (HRV) and heart rate recovery (HR2), breathing rate and volume, movement, step count, cadence, stride, activity level, calories burned and sleep quality. According to the supplier, the system has found research application in the areas of cardiac, respiratory, activity analysis (such a steps, cadence and calories, stress, cognitive and sleep). Abdallah et al. [38] applied Hexoskin biometric vest to measure ventilation (VE), tidal volume (VT), breathing frequency (Bf), inspiratory capacity (IC) and inspiratory reserve volume (IRV) of a small cohort of adults with Chronic Obstructive Pulmonary Disease (COPD) at rest and during exercise; and found them to be valid when compared against the data collected by a pneumotachograph (Ptach). Al-Sayed et al. [39] compared the heart rate monitoring capacity of the Hexoskin biometric shirt and Polar H7 heart rate sensor through a study involving twelve volunteers and reported no significant difference between two systems. Banerjee et al. [40] employed Hexoskin vest to estimate physiological measures such as heart rate, breathing rate, lung volume, step count, and activity level of thirty-one participants aged 65 and older and compared the collected data against the clinically accepted gold standard values. They concluded that heart rate, breathing rate and step count collected by Hexoskin showed strong correlation against the gold standard measures, but lung volume and activity level measures did not.

c) OM Signal

OM signal from Canada offers SeCS with embedded ECG, respiration and physical activity sensors [12]. The system contains printed ECG sensor on the inner surface of the clothing. The e-module is attached on the left side under the chest area of clothing (Shirt, Camisole and Bra). This records consumer's biosignals and streams them wirelessly and in real time to the consumer's smartphone via Bluetooth. The data is also automatically sent to the cloud platform of internet, where it can be further analysed using advanced algorithms and artificial intelligence (AI). Porbabee [41,42] applied this system in ECG based human identification and mental stress prediction using heart rate variability. However, the system is yet to be offered commercially.

d) Emglare

Emglare from California, USA offers an SeCS with fully integrated heart rate and EC sensors, non-detachable battery for wireless charging and Bluetooth antenna [13]. The intelligently designed vest hosts two ECG sensors and one heart rate monitor at the chest area in the front and an automatic power switch near the left armhole. The Bluetooth antenna, battery and the wireless charging component are hidden at the centre back of the clothing. Once a consumer wears the vest and turns on the Emglare mobile app, the smart vest starts sending heart rate and ECG data automatically to the app. The system stores health statistics on daily and weekly basis, which can be shared with others. The application automatically sends a notification if the heart rate is higher than usual and can inform connected doctors, relatives or friends about it. Although it looks very smart in design and activity, the system is yet to reach consumers' hands. However, the company in accepting online pre-order now.

e) Master Caution® from Healthwatch

Master Caution® from Healthwatch Technologies, Israel offers a 12-lead ECG monitoring garment with FDA-clearance and CE-approval [14]. The system can monitor heart activity, respiration, fall detection, movement and temperature. The design is based on wearable textile-electrodes and heart-sensors and contains digital health diagnostic services including mobile cardiac telemetry, patient monitoring tele-health services and other services that allow for in-home medical services. Master Caution® continuous monitoring solutions assist clinicians in remotely monitoring their elderly or bed-ridden patients. It can alert of cardiac events such as ischemia and arrhythmias in near real-time, using the automatic analysis (AI) system, and thus securing personal health around-the-clock for improved patient safety. According to the supplier, the offered garment is machine washable, with at least 50 washing cycles and available in a full size range for men and for women.

f) Siren diabetic socks

Siren from San Francisco offers socks with embedded temperature sensors that can help detect foot ulcers early in diabetic patients [15]. It uses temperature micro-sensors integrated into textiles that can detect changes in temperature at the bottom of the feet. A small tag attached to the sock reads this temperature gradient data and wirelessly transmit it via Bluetooth to a specific app. Study by Armstrong et. al. [43] shows self-monitoring of foot temperature may reduce the risk of ulceration in diabetic patients.

g) Neopenda baby hat

The New York based company, Neopenda, aims to fight the sudden infant death syndrome (SIDS) in developing countries, namely Uganda. It offers a baby monitoring hat that makes it possible for nurses to monitor several infants continuously and simultaneously; thus, reduces newborn mortality [16, 30]. The baby hat is embedded with an e-module at the front and is able to measure temperature, heart rate, respiratory rate and blood oxygen saturation of the infants. The device can transfer vital signs to a central monitoring system via Bluetooth transmitter. The system is designed to monitor up to twenty-four babies through one monitor.

h) Mimo from Rest Devices

Similar to Neopenda, Mimo from Rest Devices (USA) is a baby breathing and activity monitoring kit that includes machine washable kimonos of a specific size (0-3, 3-6, 6-12 months), one Lilypad (charging & WiFi base station), one low-power bluetooth transmitter called turtle, and charging and power cables [17]. The e-module is in the shape of a green turtle and snaps onto the front of the onesie, and can monitor baby's breathing, body position, sleep activity and skin temperature. Mimo data strips pick up subtle movements in baby's breathing and activity and transmit those to the Lilypad, which sits near the baby while plugged into a wall. The Lilypad picks up baby's coos and cries through an embedded microphone, and sends that live audio, along with all other data, securely to a server then straight to parents' smart devices, where they can see, in real-time, how their little ones are doing.

i) Bioman+ from AiQ

The Taiwanese company AiQ smart clothing offers a variety of smart garment, under the general name Bioman+, with integrated 1-3 lead ECG monitoring system for health monitoring of patients, elderly people and sportspersons [18]. It is an upper body garment solution that consists of conductive fibre based textile electrodes for the acquisition of the electric activity of human body and conductive thread to carry the electric signals to the processing and transmission module that is snapped onto the garment. It is available in several styles – vests, t-shirts and sportbras - with five different types of electrode structures suitable for different user scenarios and three fabric variants with different levels of compression. The company claims to have used stainless steel fibres, yarns and threads, omitting the need for an additional copper or silver coating, to simplify manufacturing [44].

j) Skiin from Myant Inc.

Canadian company Myant Inc. offers smart fabrics under the brand "Skiin" that are claimed to be comfortable and washable, and able to monitor ECG, HRV, breathing patterns, stress levels, sleep quality, steps, distance, calories burned, active minutes and stationary time all day and night. For female consumers, it also can identify the fertility window by monitoring the changes in skin temperature and resting HRV to maximise the chances of getting pregnant [19]. The company has presented design of underwear in classic cuts in varying fit for both men and women. Each undergarment has a slit in the waistband where the smart device can be inserted to track the health of the wearer [45]. The device can be charged wirelessly. The company is offering smart fabrics and smart solution for retailers, therefore the final product is yet to be available commercially.

k) Neuronaute® from BioSerenity

The French company BioSerenity offers a SeCS called Neuronaute® for diagnosis and monitoring of patients with epilepsy in their own home [85, 86]. The system consists of a smart t-shirt and a smart cap containing EEG, ECG and EMG sensors and 9-axis accelerometer. This top and cap outfit can detect electrical activity from the brain, heart and muscles of its wearer and send to smart phone or to doctors via Cloud [90,91]. The system obtained CE marking in 2016 after a six-month trial at the Brain and Spine Institute at the Pitié-Salpêtrière Hospital in Paris [85,86,].

l) Others

The British company Smartlife offers a textile sensor technology that can be integrated into comfortable active wear [20]. The company claims their device, called the Brain, to be small and discrete, allowing communication with third party apps. The textile sensors and smart device offered are able to monitor ECG signals, impedance pneumography, impedance plethysmography, surface electromyogram and accelerometry for 12 hours.

The American company Sensoria offers SeCSs that can be of help for people suffering from gait impairments, short stride lengths and slow walking speeds. The Sensoria®Walk app works in conjunction with electronic anklet, and textile sensor infused smart socks to help its wearer set goals, track daily activities including steps, cadence and distance during rehabilitation after a stroke or post-surgery, with the ultimate goal of speeding up overall recovery time. As reported by Gaibizzi et al. [46], Sensoria smart t-shirt could potentially be a promising candidate component, that is compatible with the Heart Sentinel™ smartphone app, to build a system for detecting and alerting cardiac arrest caused by life-threatening arrhythmias such as ventricular fibrillation (VF) during outdoor sports. A study by D'Addio et al. [47] on posturographic assessment with a small group of patients having Parkinson disease identified Sensoria fitness e-textile socks as a low-cost alternative to evaluate variations in centre of pressure (CoP) signal when compared with gold standard stabilometric Zebris platform (ZP).

3.2 SeCS for sports

Five suppliers of SeCS have been found to be active in the sports industry (see table 5). Except Komodotec, all other offer clothing items for sportsmen, sportspersons. Komodotec offers a compression sleeve for arm, which encaged an e-module into it. Again, knitted fabric is the common feature of the textile components of these products.

Table 5: Features of the textile components (TCs) of available SeCSs for sports training

#	Supplier	Textile Component (TC)				Ref.
		Type	**Key Design Features**	**Fabric Structure**	**Other features**	
1	Athos	Men's Shirt	Long sleeve, e-module snaps into the centre of front chest area	knitted	sweat-wicking technology, compression	[21]
		Men's Shorts	Elastic waist, e-module snaps into the side of thigh area			
		Women's Legging	Elastic waist, e-module snaps into the side of thigh area			
2	Medtronic (Zephyr)	Compression T-shirt	Sleeveless, long length, Centre chest e-module location, tight fit	Knitted (84% PES, 16% Spandex)	conductive metallic fabric used as sensors, Stretchable	[22]
		Sports Bra	Securely sewn on back of bra with a neoprene backing to protect skin and e-module sensor, Stretchable, medical-grade wiring connects sensors, e-module sensor on the back.	Knitted (88% PES, 12% Spandex)		
		loose fit shirt	Left side e-module location, semi-fitted athletic style, male and female fitting	knitted	flame resistant, quick drying, machine Washable at cold water (30°C)	
3	Polar Team Pro	Sleeveless T-shirt	Fits fairly tight so that the electrodes are firmly against wearer's skin	knitted	machine washable at 40ºC/104ºF, No spin-dry, iron, dry clean, no bleach or softener	[23]
4	Komodotec	Compression Sleeve	sleeve with built in sensor on biceps and attachable device	knitted	Machine washable - 100 times.	[24]

5	Sensoria	T-shirt	Short sleeve, tight fitting	Knitted (92% Polyamide, 8% elastane)	breathable, moisture wicking fabric, antimicrobial, machine washable	[25]
		Vest	e-module is attached with standard snaps at the centre of under chest, knitted wrinkle-pattern at front and back to ensure compression	Knitted (95% polyamide and 5% elastane)		
		Sports Bra	Elastic band, e-module to be attached with standard snaps at the centre of under chest	Knitted (74% polyamide, 18% polyester and 8% elastane)		
		Socks with anklet	detachable anklet that snaps onto the sock	knitted		

Table 6: Features of the electronics modules of available SeCSs for sports training

#	Supplier	E-Module						Sensing Parameters	Battery			Ref.
		Device Name	Weight (g)	Dimension (mm)	Data transfer	Assembly with TC	Compatible App/Software		Type	Life (hr)	Charging	
1	Athos	Core	22	Oval shape, small	Bluetooth	snaps into socket on Athos garments	Athos iOS app	sEMG, heart rate, calorie expenditure, and active time versus rest time.	-	10	USB	[21]
2	Medtronic (Zephyr)	BioModule	18	48 x 46 x 10	Bluetooth low energy and gateway	plugs into garment	OmniSense desktop software for windows	ECG, respiration, body temperature, accelerometery, time and location	Li 3.6 to 4.2V	24	USB	[87,88]
3	Polar Team Pro	Polar Team Pro Sensor	39	small	Bluetooth	slides into garment at CB of neck	iPad app and web service	motion sensor, heart rate, GPS	Li-poly	10	Charging dock	[89]
4	Komodotec	AIO device	-	small	Bluetooth	snaps into place at wrist	AIO sleeve app for android and apple	sleep analysis, health score, blood oxygen saturation level, ECG	-	-	-	[24]

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5	Sensoria	HRM	-	small	Bluetooth Smart, ANT+	connect to snap buttons under chest	Sensoria Fitness App, compatible with 3rd party apps	heart rate	-	-	USB	[25]
		Anklet	<28	Covers half ankle	Bluetooth	magnetically connect to socks, fold sock over anklet		cadence, foot landing and impact forces, step counting, speed, calories, altitude and distance tracking	-	6		

a) Athos

Athos system from Mad Apparel Inc. (USA) includes compression shirt and a detachable e-module, which offers real-time biometric tracking, including muscle activity, heart rate, calorie expenditure and active time versus rest time [21]. It tracks exertion of the major upper-body muscle groups: pecs, biceps, triceps, deltoids, lats and traps. When snapped on the Athos apparel, its e-module can collect and analyse data from the garment's sensors and delivers that data to user’s mobile app via Bluetooth. The proprietary software can display which muscles are firing and how much they are being exerted; distribution of work by muscle group, from left to right, to detect if the user is overworking or compensating as a result of poor form; and helps understand how muscles are contributing to the movement. It is reported by the supplier that athletes from different professional league in the USA including the Philadelphia Phillies (MLB), LA Clippers (NBA), FC Dallas (MLS) and Ohio State (Collegiate Division 1) use this system for training purposes. Lynn et al. [48] studied surface electromygraphy (sEMG) measurements from twelve healthy subjects taken by Athos compression garments with built-in EMG electrodes and research grade Biopac bipolar Electrodes (Biopac Systems Inc., California). Their findings showed no significant differences between normalized EMG amplitude or in strength of the relationship between sEMG and torque output between Athos and Biopac.

b) Zephyr from Medtronic

Zephyr™ performance system from Medtronic (USA) is a SeCS designed to support training of athletes, military and first responders. The system can read six parameters (ECG, respiration, estimated core body temperature, accelerometry, time and location) of its wearers and can process

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them to report twenty one biometrics [heart rate, breathing rate, heart variability, HR confidence, estimated core temperature, impact, activity, posture, caloric burn, % heart rate, % heart rate anaerobic threshold (AT), accelerometry, physiological and mechanical intensity loads, training loads and intensity, jump, explosiveness, peak force, peak acceleration, GPS speed, GPS distance and GPS elevation]. The combination of these biometrics can yield nine biomarkers of a wearer, which are: 1) fatigue (HR recovery), 2) readiness (HRV), 3) safety (maximum HR, core body temperature, location), 4) over-training and under training (intensity and load), 5) fitness improvement (VO_2 max, HR @AT), 6) caloric expenditure and burn, 7) agility (accelometry, speed and distance), 8) athlete management (intensity and load) and 9) stress (HRV). Its sensor module known as BioModule^{TM} can be worn via compression shirt and sport bra or a strap. Nazari et al. [49] through a systematic review of literature identified ten research studies focusing on the reliability and validity of heart rate measurements taken by Zephyr device and concluded that the device displayed good agreement with gold standard measurements.

c) Polar Team Pro

Polar Team Pro offers a team-based solution for athletes and their trainers [23, 89]. The performance tracking sensor embedded in the garments is able to track motion, heart rate and location through GPS. All information gathered by the garment is then sent to a tab, allowing the coach of a sports team to evaluate all their players at once and from a distance of up to 200 meters [50].

d) Komodotec

Komodotec offers a smart compression sleeve, which can be paired with a separate sensor device to track heart rate, analyse sleep patterns and provide full-time ECG monitoring [24]. The company claims the sleeve is easy to wear and does not interfere with everyday life. Based on heart rate variability, the sleeve can give information about the body's reaction to alcohol or drugs, recovery status, the wearers stress level and their reaction to food.

e) Sensoria

The running system from Sensoria including smart t-shirt or sport bra and smart socks, and supports professional runners with their training and coaching [25]. The Sensoria Run mobile app allows them to tailor your goals and track your progress and the Sensoria Virtual Coach literally monitors every step and provides actionable audio and video feedback during running. It can help professional runners to improve their running mechanics by telling them when they are in the correct and incorrect running positions.

3.3. SeCS for fitness

Although there are several wrist-worn wearable systems that support fitness activities and tracking are available on the market, only a handful of SeCSs are there to serve this sector, as can be seen in the table 7.

Table 7: Features of the textile components (TCs) of available SeCS for fitness tracking

#	Supplier	Textile Component (TC)				Ref.
		Type	Key Design features	Fabric Structure	Other features	
1	Sensoria	T-shirt, Vest	Short sleeve, tight fitting	Knitted (92% Polyamide, 8% elastane)	breathable, moisture wicking fabric, antimicrobial, machine washable	[25]
		Sports Bra	e-module snaps at the centre of under chest, knitted wrinkle-pattern at front and back to ensure compression	Knitted (74% polyamide, 18% polyester and 8% elastane)		
		Socks with anklet	Elastic band, e-module to be attached with standard snaps at the centre of under chest	knitted		
2	Wearable X	Yoga Pant	e-module clips into the pants behind the left knee, flat seamed	Stretch, compression Knitted	integrated sensors and haptic feedback (vibration) system, gentle Wash and Tumble Dry	[26]
3	Supa	Sport Bra	classic racerback style finished with soft black elastic band	Knitted (95% PES, 5% Lycra)	Machine wash cold, hang dry and do not iron, do not bleach. Remove the SUPA Reactor before washing! Rinse the SUPA Reactor after 2-3 uses.	[27]
4	Syngal/ Broadcast wearables	T-shirt	Short sleeve	Knitted	dry-fit, soft switch, vibration sensors for navigating	[28]

Table 8: Features of the electronics modules of available SeCSs for fitness tracking

#	Supplier	E-Module				Sensing Parameters	Others	Ref.
		Device Name	Data transfer	Assembly with TC	Compatible app/Software			
1	Sensoria	HRM	Bluetooth Smart, ANT+	connect to snap buttons under chest	Sensoria Fitness App, compatible with 3rd party apps	heart rate	-	[25]
		Anklet		magnetically connect to socks, fold sock over anklet		cadence, foot landing and impact forces, step counting, speed, calories, altitude and distance tracking		
2	Wearable X	Pulse	Bluetooth	clips into the host plate behind the left knee	Nadi X app	movement	USB charging, power need 370mA	[26]
3	Supa	Reactor	Bluetooth smart	snaps to front under bust band	SUPA.AI app	heart rate	CR2025 Lithium coin cell, life 500hrs	[27]
4	Syngal/ Broadcast wearables	BLE module	Bluetooth	sewn into garment	Syngal android app	GPS, calories, stairs climbed	washable	[28]

a) Sensoria socks

In addition to the smart shirts described in the section 3.2e, Sensoria offers smart socks with integrated textile pressure sensor technology [25], when paired with a Bluetooth enabled anklet, it can track user's steps, walking time and distance on a daily basis. The accompanying application allows to set independent goals on each metric an user wants to track. The anklet is detachable whilst the socks are infused with proprietary textile sensors. This allows the socks not only to monitor step counting, speed, calories, altitude and distance but also cadence and foot landing technique whilst exercising.

b) Wearable X

Wearable X, an Australian American company, offers leggings, branded as "Nadi X", with knitted accelerometer and haptic feedback technology for yoga training. It can track wearer's goal, performance and progression to help personalised yoga training in real-time yoga session [26]. In conjunction with its electronics component that integrates battery and Bluetooth data transmitter, the yoga pants can generate gentle vibrations to guide wearer with yoga poses and can act as a yoga coach when paired with Nadi X iOS app.

c) Supa

The streetstyle brand Supa from USA offers a sports bra with integrated textile heart rate sensors [27]. The e-module, called SUPA reactor, can be attached to the sports bra and is then connected to a proprietary app (SUPA.AI). As this system is made for active wear, the smart device is water resistance and can track workouts by monitoring the heart rate of the wearer, similar to a sport monitoring chest belt. It is also supported by artificial intelligence within the application.

d) Syngal t-shirt from Broadcast Wearables

This t-shirt by the Indian company Broadcast Wearables, is being offered for the use during exercise and everyday life or in traffic [28]. The garment is able to track steps and floors climbed. It also provides how many calories are burnt and distance achieved during exercise. Additionally, the t-shirt can help the wearer navigate in traffic. The company claims that the t-shirt vibrates slightly on the wearer's shoulders to indicate the direction to turn. Compared to other garments in this category, this t-shirt does not include a heart rate monitor.

3.4 SeCS for Social

Other than health, sport and fitness sectors, there are a few SeCSs, which can assist in communication, entertainment and leisure activities of their users.

a) Trucker Jacket by Levi's & Google

American companies Levi's and Google jointly presented a smart jacket that facilitated a smooth commute for cyclist in big cities. With conductive yarns woven into the sleeve of the jacket, it works as an electronic platform. Digital connectivity is provided through the snap tag attached to the jacket's cuff. The snap tag, which is positioned at the cuff of the left sleeve, can communicate with the wearer through light and haptic feedback. The companies claim that the battery of the tag lasts up to two weeks and can be charged using USB. It is also claimed that wearing the trucker jacket, consumers will be able to connect to their digital life instantly and effortlessly. With a lateral brush of the cuff, the wearer can handle calls and texts without handling the mobile device, navigate and play, pause, and skip through their favourite music [51, 52].

b) Spinali Design

The French company Spinali Design offers different clothing range and swimsuits having embedded sensors for intelligent functions [32]. One of those functions is UV warning to the wearer via smartphone app to apply sunscreen. Its IOS/Android associated system "the Neviano UV Protection" comes with the functions like "weather", "pics", "suntanning tips", and "sunscreen alert". The application integrates a function called "Valentine" that alerts users' partners when to apply sunscreen to the users while sunbathing.

4.0 Development in wearable sensors

Wearable sensors mainly integrate wireless sensor technology. With on-board processing and miniaturised electronic transducer, such sensor technology has enabled whole new realm of modern day living. Benefited by wireless sensor network and cloud communication, such technology is coined as Internet-of-Things (IoT) [53]. The essential module of a wearable sensor system includes sensing element, signal condition module, core computational unit and wireless communication protocol. In actual industry, microcontroller is the main option to develop wearable sensors, due to their rapid-prototyping and economic characteristics. Electronic manufacturers such as Nordic Semiconductor, Cypress, PIC, Texas Instrument, Freescale have their own roadmap and customers' preferred solution in developing microcontroller that are suitable for development of wearable sensors.

4.1 Sensing element in wearable technology

Usually wearable technology consists of several common sensing elements: accelerometer, magnetometer, gyroscope and optionally, an ECG electro-pad. A combined package of accelerometer, magnetometer and gyroscope are common in use due to their volatile application and prices. These combination is termed as 9-axis intertial motion unit (IMU) sensor. STMicroelectronic's LSM9DS1 [54] and Bosch's BMF055 [55] are two examples of such IMU sensors. ECG sensor features conductive electrodes that needs to be physically in cotact with human skin. Research shows conventional pre-gelled Ag-AgCl electrodes offer high signal-to-noise ratio (SNR) and reduce skin impedance [56, 57]. Additional electronic circuits are required to ensure maximum transfer of power and amplification.

4.2 Communication protocol and power consumption

The main candidates for energy consumption are embedded microcontroller and wireless module. Embedded system-on-chip has relatively low energy consumption compared with conventional monitoring system. The high-end micro-controllers (32bit) have promising energy-aware characteristic, which maintain their current draws at full operation mode at around 25mA [58-60]. 8-bit microcontrollers have lesser power consumption (5mA to 10mA) but their computational capabilities are limited [61]. Sleep or hibernate features are integrated as handy user modules to provide better power characteristic. As a wireless communication module, XBee consumes around 50mA when transmitting or receiving remote signals [62]. In sleep mode, the energy is conserved to 1mA. In recent growth of BLE (Bluetooth Low Energy) 5.0, latest microcontroller emebedded great wireless capability and it is highly believed to be the next candidate of IoT communication protocol.

In energy aware features, the power budget for the energy consumer devices must be studied wisely as the ambient energy from a harvesting module is limited. The performance of the wearable sensor is proportional to power consumption. Table 9 presents the power consumption data for some common monitoring sensors.

Table 9: Power consumption data for some monitoring sensors [63-65]

Sensors	Current consumption		
	Transmission mode (mA)	Reception mode (mA)	Sleep mode (µA)
IMOTE2 (Crossbow)	33	33	390
DataBridge wireless I/O modules	37 to 120	37 to 120	<100
Apex and Apex LT modules	170	37	5
Si4420 Universal ISM Band FSK Transceiver	13 to 26	5 to 11	0.3
XBee 802.15.4 modules	50	50	10
MCU with Bluetooth Low Energy 4.2	7	7	0.1
MCU with Bluetooth Low Energy 5.0	7	7	0.1

4.3 Sustainability

Power supply is one of the critical factors to sustain the operating time of wearable technology. As reported in [66], the battery energy density has slowest improvement multiples compared with other computer technology development. Hence, Paradiso et al. [66] emphasised that the research direction for power management lies on the efficient power management in sensing nodes, thus reducing required energy volume.

4.4 Memory and computational capability

Due to limited space in microcontroller, most of the available wireless wearable sensor systems do not have large memory and high computational speed for advanced algorithm. Most of the wearable sensors depend on their master device for data trending purpose, in this case there are mobile phones, sensor gateway or computer. Thus, wireless communication of the developed device becomes a critical factor to ensure continuous data storage and transfer.

In terms of sensor functionality, many publications did not discuss the memory limitation and processing speed to carry out signal acquisition and processing [68, 69]. This is very crucial in embedded system as the resource for memory and computational core are strictly limited for

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performance and power management. Many studies on energy harvesting did not clearly address the power consumption characteristics of energy consumer modules [70-72].

5.0 Textile based sensors

The electrical potential generated by human organs such as heart, muscles, brain can be sensed on the skin. This requires the integration of flexible conductive materials at the close vicinity of skin. Compression garments are usually conforming the body of the wearer with a thin, breathable and comfortable fabric. To measure cardiac bio-potential (the ECG), conductive materials are used as sensors that can be integrated in compression garments, chest strap and adhesive body patches. The physical and electrical characteristic of conductive materials is directly correlated with skin to electrode impedance and its ability to sense the signal accurately. This section of the paper describes different materials characteristics and their structures used in literature to sense vital signs from human body.

5.1 Wet electrodes

Commercially, wet electrodes are sued to measure the ECG signal from the heart activity. The commercial electrodes are comprised of several functional layers. The conductive Silver/Silver-Chloride (Ag/AgCl) ink is printed on an adhesive paper and an ionically conductive gel (typically hydrogel) is coated on the conductive Ag/AgCl layer. The ionic gel creates the ionic bridge between the body and the electrodes and lowers the skin to electrode impedance. Additionally, the AgCl salt in the conductive ink also helps to maintain the ionic bridge network between the skin and the electrode. The skin alike soft gel material can enhance the adhesion of the electrodes with the skin and thus minimise motion artifact of the signal. However, the commercial sticky sensors are used as disposable electrodes since it can create discomfort and noticeable body rash if used for long time [73]. Therefore, dry electrodes are heavily studied in literature as replacement of commercial wet electrode for long time monitoring of vital signs.

5.2 Printed dry textile electrodes

Screen printed conductive ink directly on substrates like, film, textile, nonwoven materials is used as a simple and common technique to develop sensor electrodes for measuring ECG or other vital signs. Increasing the surface area or the electrode can potentially decrease the skin to electrode impedance

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and provide reasonable signal with comparable SNR as wet electrodes [74]. Ag/AgCl ink is dominantly used for screen printing dry electrode to enhance the ionic conductivity and lower skin to electrode impedance, although this requires the generation of sweat on the skin. Dry electrodes show promise in literature as durable sensor electrodes for long time monitoring, however, the signal quality deteriorate drastically when the wearer is in active mode such as walking, running since dry electrodes cannot create a good adhesion on the skin like wet electrodes. Integrating dry electrode at the strategic locations (where the body muscles do not move much during active modes) in compression garments to enhance signal quality [75]. Other than, conductive Ag ink and Ag/AgCl ink, functional materials such as carbon, [76] conductive polymers such as PEDOT: PSS [77] are used as well in the literature to measure signals like ECG. These active materials are directly screen printed, inkjet-printed [78] or dip-coated [79] on textile to develop wearable sensor electrodes.

5.3 Dry electrodes from conductive threads

Electrically conductive yarns can be integrated in the fabric structure to develop conductive patch that can also be as textile sensors to measure human physiological vital signs. The whole garments knitting technology can enable developing a garment with diverse design without the need to cutting and sewing. This platform technology can integrate conductive yarn and knit sensor patched in the designated location of a garments. Knitted sensors improves the wearer comfort such as breathability, however, requires high compression to detect quality signal [80]. Additionally, technology like embroidery of conductive yarn on a textile can create dense conductive patterns on a textile surface and create cushiony structure to impart compression on the sensor location to improve signal quality [81].

5.4 Inonotronics

Other than these common materials and manufacturing process, recent development of ionically conductive inkjet printable materials show great promise for manufacturing biosensors on different substrates including textiles. The combination of inkjet-printed conductive polymer electrodes and ionically conductive materials on top as a coating lowers the skin to electrode impedance and improve SNR of the signal [82]. It is already mentioned that the ionically conductive and tacky hydrogel material is used in almost all commercial electrode to lower skin to electrode impedance, improve ionic conductivity and lower motion artifact. However, these gel materials are not durable and dry out over the time. Recent development of durable, tough and conductive hydrogel opens the new avenue of electronics called "ionotronics". These materials already show superior result to sense bio-signals (including ECG) from human skin and long time.[83] However, the multiple manufacturing steps and integration challenge of this materials with other soft materials such as textiles are yet to be progressed for commercial applications.

5.5 Gecko-like dry electrode

The concept of creating a secondary skin-like materials that act as sensors and feels like skin poses a unique idea for building biosensors. The development of gecko-like dry adhesive with conductive functionality shows promising result to monitor bio-signals from skin in real time during heavy action period of the wearer. The literature shows the development of conductive soft silicone materials with micro-patterned top surface can adhere to human skin simulating the gecko feature [84]. The sensor shows significant improvement of motion artefact, which is a great challenge for the class of dry electrodes.

5. Conclusion

With growing expansion of IoT application in various fields, experts predict potential niche market of IoT technology for smart clothing. Trend in wearable technology is to have them embedded within clothing, known as wearable 2.0, which is also envisaged to be convenient, comfortable, washable, highly reliable and durable. A presented wearable electronics are mounted on textiles, but not fully embedded into textiles. They are only washable now, when electronics components are removed from them. There has so far been no study reported how the rigid electronic components influence consumers' comfort perception. Another significant research problem is the energy sustainability and battery size, to move towards true Wearable 2.0.

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Author Contributions

Abu Sadat Muhammad Sayem (ASMS) conceptualised the research study and the paper. All authors including ASMS contributed in literature research and paper writing.

Conflicts of Interest

The authors declare conflict of interest.

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