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Review—Smart Wearable Sensors for Health and Lifestyle Monitoring: Commercial and Emerging Solutions

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The rapid growth of urbanisation has brought about various health concerns for citizens living in urban environments. Sedentary lifestyles, increased pollution levels, and high levels of stress have become prevalent issues affecting the overall well-being of urban populations. In recent years, the emergence of smart wearable devices has offered a promising avenue to address these health concerns and promote healthier lifestyles. This review evaluatse the effectiveness of smart wearables in mitigating health concerns and improving the lifestyles of urban citizens. The review involves 50 relevant peer-reviewed smart wearable studies and supporting literature from electronic databases PubMed, Ovid, Web of Science, and Scopus. Results indicate that smart wearables have the potential to positively impact the health of urban citizens by promoting physical activity, tracking vital signs, monitoring sleep patterns, and providing personalised feedback and recommendations to promote physical activity levels. Furthermore, these devices can help individuals manage stress levels, enhance self-awareness, and foster healthier behaviours. However, the review also identifies several challenges, including the accuracy and reliability of wearable data, user engagement and adherence, and ethical considerations regarding data privacy and security.
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The physical environment we live in shapes our everyday disposition and activities. As cities are dense conglomerations of individuals interacting within an ecological network, city citizens are exceedingly sensitive to numerous factors affecting their perceived safety and feelings of well-being. Many metropolises in the developed world are deficient in clean air, green space to navigate outdoors, innocuous exercise routes and safe contact points, which can have a detrimental influence on an individual's physiological and psychological well-being.[1] The safety concerns associated with outdoor physical activity in urban environments further exacerbates the challenges faced by urbanites who seek to maintain a healthy lifestyle.[2] Numerous concerns are around chronic disease susceptibility, pollution and lack of green space, which contribute to feelings of insecurity and discourage people, particularly among vulnerable groups from engaging in outdoor exercise.[3] Addressing these safety concerns is crucial to promoting active lifestyles and creating environments that support the health and well-being of urban residents.

In addition to the above, in metropolitan cities around the world, there are further issues relating to physical activity and well-being. Built environments negatively affect the populace's health and the quality of outdoor physical activity undertaken.[4] The World Health Organisation[5] reported two million global deaths a year, as are result of an insalubrious sedentary lifestyle, a consequence of urbanites' predisposition to desk jobs, reduced green space access, excessive fast-food options, lack of physical movement and greater environmental stressors.[6] Indeed, mobility and vulnerability are two key factors affecting an individual's health, particularly those residing in urban environments, where insufficiencies within existing healthcare systems reduce the appropriate care provided.[7] Despite positive connotations surrounding increasing demographic longevity, urban elderly dwellers are amongst those who face numerous social and individual challenges in urban living.[8]

Action is needed to tackle the health crises in cities. Smart wearables, defined as internet-connected devices worn on the body, offer tremendous potential to revolutionise health care.[9] These devices provide users with versatile access to a wealth of data and information across multiple platforms. Presently, smart wearables serve a wide range of functions, including step counting, heart rate and respiratory rate monitoring, environmental tracking, and even mood assessment, all with the potential to significantly contribute to urban health improvement. While smart wearables are now ubiquitous, it's crucial to note that their historical usage was quite limited, and their development has advanced exponentially, as illustrated in Fig. 1.

The global smart wearable market growth, estimated at £42.5 billion in 2022, increased the market penetration of smart wearables into several industries, like sports, medicine, and fashion.[10] This growth enabled the multi-faceted use of smart wearables, from tracking fitness and health data to providing individually tailored notifications and alters.[11,12] Commercially available products, such as the Fitbit and Apple Watch, have significantly shaped the landscape of smart wearables. These products have gained popularity and recognition for their innovative features and potential to enhance various aspects of users' lives. Fitbit, a well-established brand in the wearables market, offers a range of devices that track physical activity, monitor sleep patterns, and provide personalised health insights.[13] Similarly, Apple Watch has emerged as a leading smartwatch, offering advanced health and fitness tracking capabilities and features like ECG monitoring and fall detection.[14] Despite the success of wearables like Fitbit and Apple, standardisation issues remain significant hurdles in the smart wearables market. With multiple platform systems and device manufacturers, achieving successful integration and compatibility among different wearables poses a complex challenge. Collaboration between disciplines is needed to address these challenges and establish common standards for smart wearables.

The primary focus of this review is to assess the potential of smart wearables in improving health within urban environments. It aims to evaluate how smart wearables can effectively contribute to the improvement of urban dwellers' health and overall quality of life. The review also explores the implications involved in the integration of smart wearable devices within the cities that would allow users to extend the usage beyond physical boundaries and induce further advancements. The integration of wearable devices into the infrastructure of smart cities can offer valuable insights into urban environments and their impacts on the populace's health.

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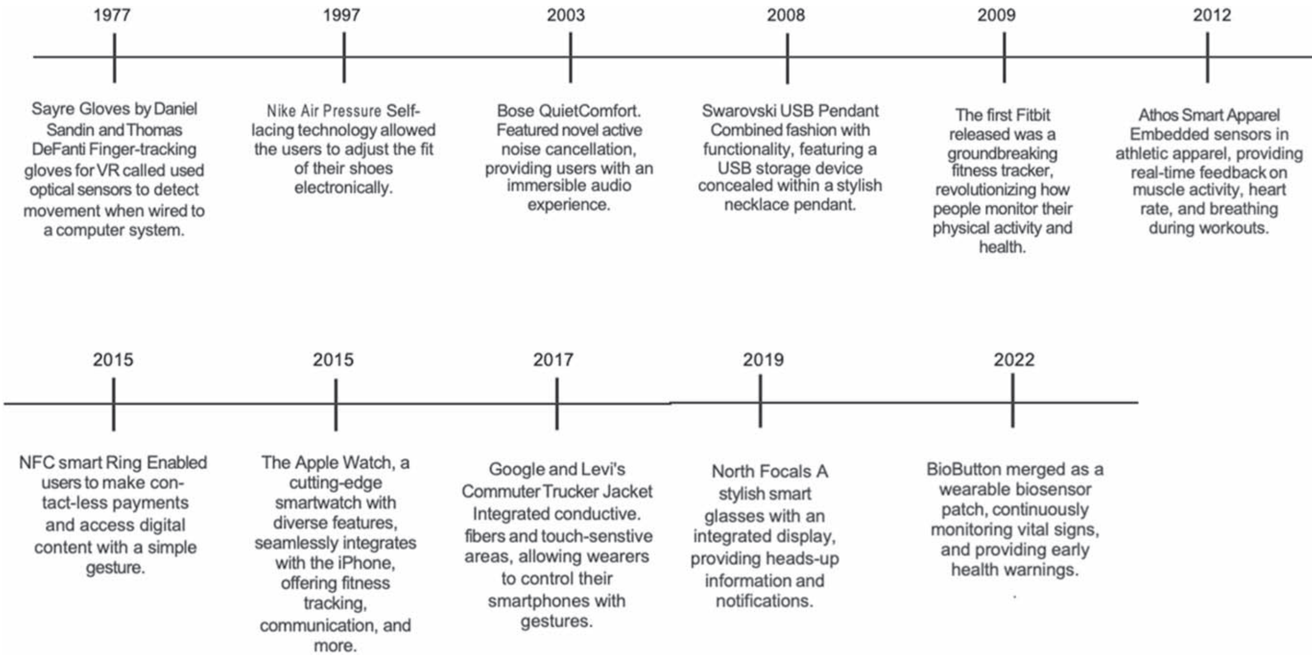

Figure 1. A Brief History of Commercial Smart Wearables; Cusack (2023).

Methodology

This systematic review assessed resources from various online databases such as Web of Science [WoS], Ovid, Scopus, PubMed, and Medline through the Web of Science platform (Fig. 2). Each database was searched using keyword combinations and subject headings structured similarly to a PICO [Population, Intervention, Comparison and Outcome] framework, an approach used to formulate well-defined database searches, reference Fig. 3. This keyword search method was applied to clarify and guide searches, ensuring a focused and systematic approach that gathered all relevant sources through keyword searches.

Database searches were restricted to peer-reviewed articles published from 2010 to March 2023 to obtain the most relevant articles relating to smart wearables. Search results were collated in referencing software (EndNote 20—Clarivate Analytics). The eligibility criteria were devised to include content written in English, relevance to the five designated subcategories, and demonstrating novel research, refer to Table II. Initial searches were screened by reading the titles and abstracts, and records were removed if they demonstrated a lack of eligibility. The lead researcher screened full texts of the remaining records. The other contributing researchers then screened the eligible studies, and the lead researcher resolved disagreements about whether a study should be included.

Discussions

This section presents a comprehensive combination of key resources (n = 50) and supporting references structured into four sub-sections focusing on smart wearable sensors. Tables I and II provide a structured overview of the included studies. Table I outlines the PICO (Population, Intervention, Comparison, Outcome) framework used to select keywords for the searches, with each database undergoing 15 unique searches utilising diverse combinations of the keywords. These searches were systematically conducted throughout March 2023, searching from 2010–2023, to maximise the identification of relevant academic resources for screening. Table II categorises the identified papers into subcategories based on their thematic areas, which were established during the initial screening process, which involved reviewing abstracts and titles and applying predefined inclusion criteria.

The succeeding discussion is structured around the following thematic sections:

Enhancing urban user health and managing chronic disease.— This section explores the multifaceted ways in which smart wearables contribute to enhancing urban health and managing chronic diseases. It presents findings from a selection of n = 15 papers focused on health monitoring and n = 3 papers centred on chronic disease monitoring. By merging these sections, the review underscores the interconnection between health monitoring and chronic disease management.

Monitoring environmental exposure.— This segment explores the success of smart wearables in monitoring environmental parameters, with a particular emphasis on urban exposure. It presents findings from a section of n = 15 papers within the urban environment search theme, which examines the role of smart wearables in analysing data relevant to urban environmental conditions.

Assessing urban pollution.— Focused on evaluating the effectiveness of smart wearables in monitoring air particulate matter and assessing urban pollution levels, this section utilises n = 12 papers from the designated subcategory. By critically assessing the findings of these studies, the review offers valuable insights into the potential applications of smart wearables in assessing and mitigating urban pollution.

Outdoor physical activity assistance.— The final section explores the role of smart wearables in facilitating outdoor physical activity and mitigating associated urban health risks. This section highlights smart wearables' diverse functionalities and potential benefits in promoting outdoor physical activity engagement. This section includes five papers sourced from the relevant subcategory.

Reference Table III for an overview of smart wearable sensors examined within the discussion. Not all smart wearable sensors from the discussion are included due to constraints in related available data and crossover functionalities.

Enhance Urban User Health and Manage Chronic Disease

Increased risk of deteriorating health, the prevalence of chronic diseases and the need for consistent care reduce mobility and increase the vulnerability of urban citizens, particularly elderly groups who often receive insufficient care.[7,8] To such health challenges, abnormal

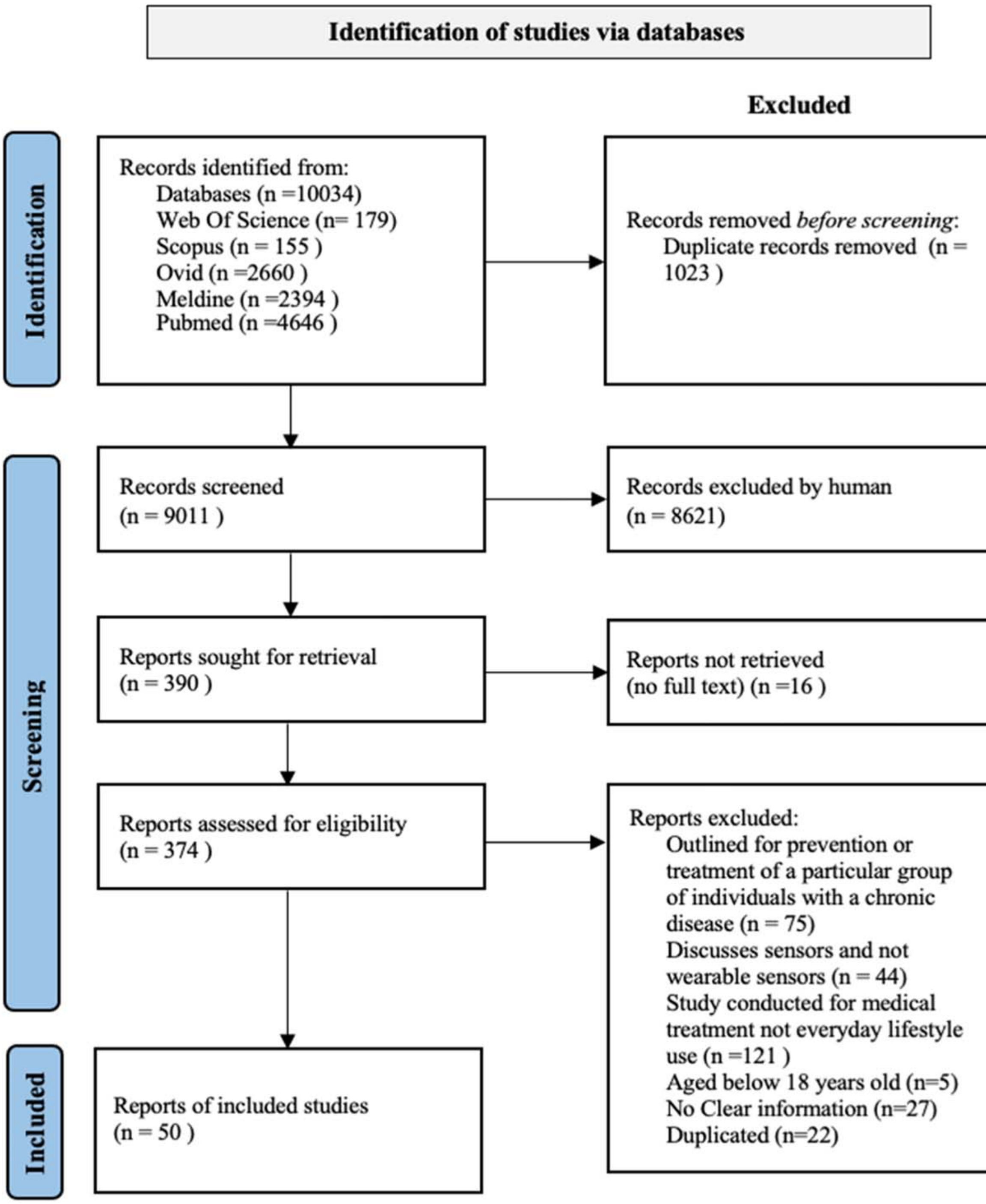

Figure 2. Database search history, (Source: Cusack, 2023).

walking detection is a common clinical practice monitored in a Human Movement Unit/Gait analysis unit. Advancements in this field and "smart insoles" have been proposed to replace cumbersome clinical devices.[15] Smart insole use cases are outside clinical settings and intend to detect the mobility of elderly users within any location to prevent possible health complications and aid safe, independent living. Previous smart insole studies have presented an 84%–96% fall detection and walking abnormality's ability, representing the successful integration of technology into a textile to prevent injury and preserve health.[15,16] Deep Learning methods and neuronic network algorithms are often applied in Smart insoles, with an easily modulated architecture that is robust and scalable. Considering the average elderly person's negative discernment of technology, adopting such a device may have certain barriers despite the electronic's discreet insole integration.[17] Concerns regarding data, ease of use and lack of understanding may lead to greater dissatisfaction levels and cause greater distress rather than facilitating health.[18] Users should feel empowered and informed when adopting smart wearable devices to monitor their physiological changes and mitigate health challenges, not distressed.

As well as physiological change monitoring, smart wearable technology has advanced to combine biological components with physicochemical detectors that can react to changes in the wearer's environment to give health advice. This could lead to developing preventative chronic and acute disease strategies over post-disease diagnosis treatment[19] (Fig. 3).

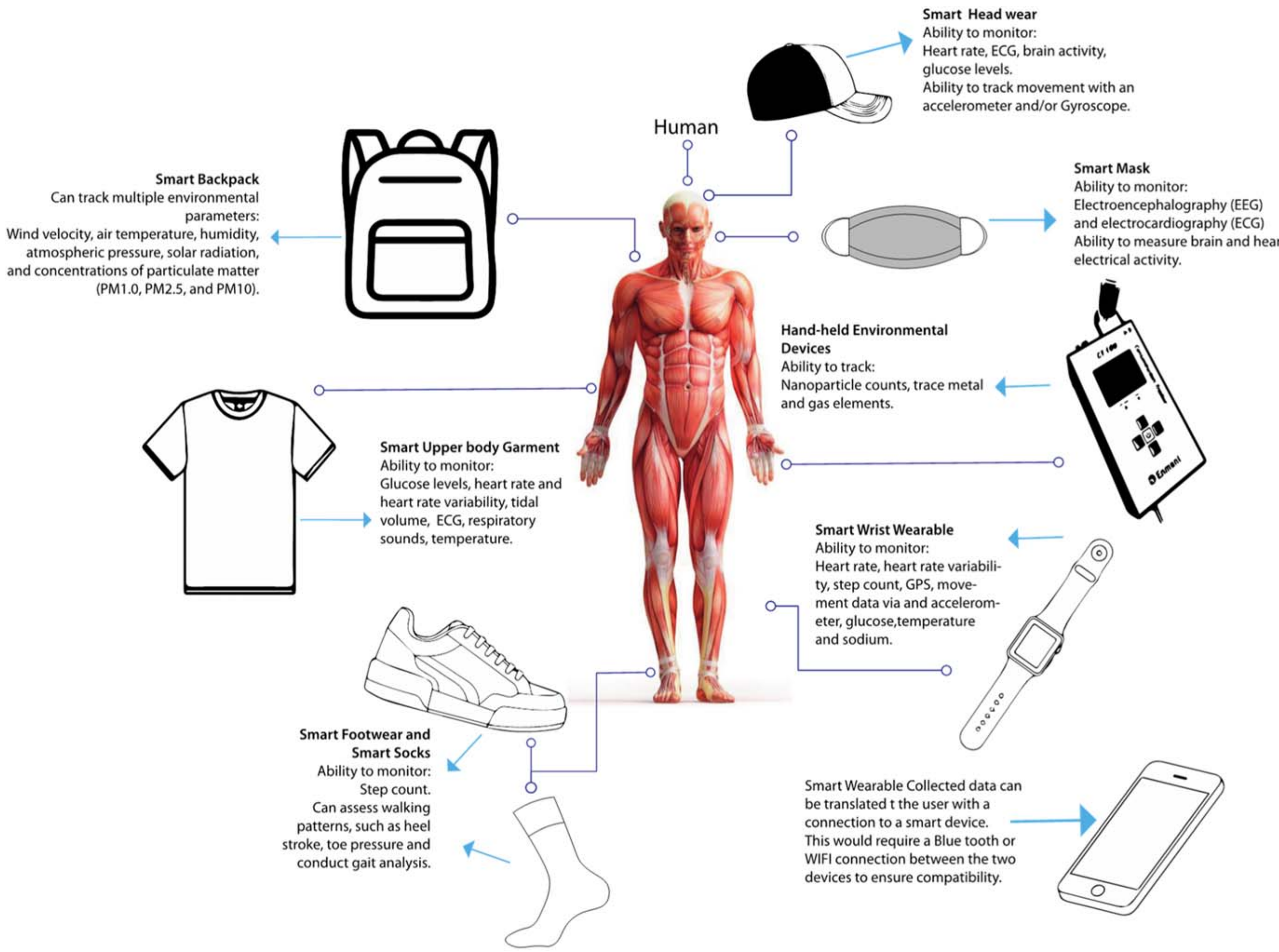

Figure 3. The potential of smart wearable devices to monitor health (Courtesy of Cusack, 2024). "Human" (Courtesy of istockphoto).

Table I. PICO framework and keywords used for searches. (Source: Cusack, 2023).

Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
Urban citizens	Smart Sensor	Air pollution	Health
Citizen	Smart wearable	Pollution	Environmental monitoring
Urbanite	Smart device	Poor health	Well-being
Urban environment	Wearable smart device		Safety
	Intelligent wearable		Physical activity
	Monitoring device		Physiological

Table II. Sub-section categorisation based on the searched papers. (Source: Cusack, 2023).

	Categorisation of searched papers					
Selection method	Health monitoring	Urban environment monitoring	Chronic disease prevention	Pollution monitoring	Outdoor urban physical activity	Total
Initial results	2311	2686	557	2111	1969	NA
Fulfilled inclusion criteria	90	75	30	137	58	NA
Final screened articles	15	15	3	12	5	50

Despite the emergence of several biological physicochemical smart wearables, their commercial viability remains limited. The *GlucoWatch biographer,* the first commercial Food and Drug Administration (FDA) approved watch for diabetic non-invasive glucose monitoring, utilises reverse iontophoresis involving an electric potential between an anode and a cathode positioned on the skin surface.[20] A skin-surface coupling device, consisting of two pressure sensors placed at two adjacent points on the body, captures

Table III. Summary of smart wearable sensor types and functions. (Source: Cusack, 2024).

Wearable Category/Name	Type	Technology	Function	User/Use Case
Smart Insole	Prototype	Deep Learning and neuronic network algorithms applied with specially designed sensors within an easily modulated architecture	Fall detection and walking abnormality detection to prevent injury and preserve health	Outside clinical settings for elderly users
CloudWatch biographer	Commercial device	Utilises reverse iontophoresis involving an electric potential between an anode and a cathode positioned on the skin surface	Diabetic non-invasive glucose monitoring	Diabetic patients
Skin-surface coupling device	Research device	Two pressure sensors placed at two adjacent points on the body, captures detailed blood pressure waveforms, detecting real-time elevated hypertension	Monitor hypertension	Pre or post hypertension patients
A photoplethysmography non-invasive wrist wearable	Research device	Uses a light source and a photodetector on the skin surface to measure the volumetric variants of blood circulation.	To identify daily heart rate spike triggers	Individuals living with heart risks
Galaxy Watch wearable	Commercial device	Multiplex of sensors; heart rate, heart rate variability, blood pressure, acceleration	Ability to monitor, step counts, sleep duration, stress, anxiety levels	Research, clinical trial and commercial use
Digital bracelet, Sanjian, Tech co, model H07	Commercial device	Two types of sensors located within a waterproof chargeable housing	Monitors steps, heartbeat rate, BP, and sleeping duration	Research, clinical trial and commercial use
Smart helmet	Prototype	Electrodes positioned at the lower jaw, forehead and mastoids	Monitoring of cardiovascular and neural activity, serving as an effective means to analyse both physical and mental conditions.	Research, clinical trial and potential future commercial use
Smart Vest	Prototype	A microcontroller interfaced with wireless communication and global positioning system (GPS) modules	Continuous monitoring of both vital signs and physical activity	Prototype but could have future clinical use case
A non-invasive breath biochemistry smart wearable	Prototype	Disposable paper-based electrochemical wearable sensor	Detect Hydrogen peroxide (H2O2)	Obstructive Pulmonary Disease (COPD) and respiratory condition patients
Empatica 4 medical wristband	Commercial Clinic device	Accelerometer, temperature, electrodermal activity, steps, blood Volume Pulse, IBI (Systolic peaks)	Medical-grade smartwatch designed to be used in clinical trials	Clinical trial use
Handheld Air beam sensors	Commercial device	Humidity and Temperature sensor Pm sensor	Measures hyperlocal concentrations of air particulate matter, temperature and humidity	Personal or research use
iButton Hydrochronic	Commercial device	Temperature and humidity sensors with 8 KB of datalog memory and data retrieval software	Monitor human-centric air temperature (TA) and relative humidity (RA)	Personal or research use
Smart backpack	Prototype	Control unit and set of sensors, selected with environmental specification and power consumption in mind, housed on a backpack	Backpack tracked multiple parameters; wind velocity, air temperature, humidity, atmospheric pressure, solar radiation, and concentrations of particulate matter (PM1.0, PM2.5, and PM10) from a hyperlocal pedestrian perspective	Research
Care service architecture	Conceptualise design	Integrated flexible sensor platforms	Communicate with medical authorities to enhance in-home health monitoring and health assessments	Research
PUFP C200	Commercial device	Semiconductor monitoring real-time nanoparticle counts, trace metal and gas elements	Personal portable particle counter	Personal or research use
Body CAP Medical	Commercial device	miniature wireless electronic sensor	Wearable connected device for physiological monitoring,	Medical, research, and sport
e-TACT	Commercial device	3D accelerometer integrated into various wearables	Allows the fine analysis of physical activity	Medical, research, and sport
My part	Prototype	A fan scattered particles over a laser onto the photodiode, generating a voltage signal enabling particle detection.	Portable personal air monitoring	Medical, research, and sport
Sniffer 4D	Commercial device			Personal or research use

Table III. (Continued).

Wearable Category/Name	Type	Technology	Function	User/Use Case
		PM1, PM2.5, and PM10, higher UPM levels monitoring, to map hyper-local air pollution information.	Designed to be mounted onto moving platforms and was incorporated into wearable research	
Sharp GP2Y1010AU0F	Commercial device	An infrared emitting diode (IRED) and a phototransistor are diagonally arranged, enabling the detection of particulate matter	Optical air quality sensor	Personal or research use
Canarin Project smart mask	Prototype	Electroencephalography (EEG) and electrocardiography (ECG) sensors measure the brain and heart electrical activity	Personal air pollution mask	Personal or research use
Integrated textile sensor	Prototype	Graphene oxide (GO) and molybdenum disulphide (MoS_2), e-textile sensors fabricated by a modified dip-coating method	NO_2 detection	Personal or research use
Sense wear band	Commercial device	An infrared emitting diode (IRED) and a phototransistor are diagonally arranged enabling the detection of reflected light of particulate matter	Portable optical air quality sensor, designed to sense dust particles	Personal or research use
Smart Sock	Prototype	Pressure sensors, conductive lines, and a block for data acquisition; communicates via Bluetooth	Assess the risk of accidents or the health condition or determine overall well-being	Medical, research, and sport

detailed blood pressure waveforms, detecting real-time elevated hypertension.[21] A non-invasive, photoplethysmography wrist wearable uses a light source and a photodetector on the skin surface to measure the volumetric variants of blood circulation. Identifying daily heart rate spike triggers.[22] These examples highlight the technological potential of smart wearables to address chronic diseases and health concerns. However, none of the devices have achieved market success despite their technological success. They are highlighting the need to consider consumer inputs, like design preferences and technological concerns, when designing smart wearables.

Indeed, user input plays a pivotal role in the success of various devices. The step counts, sleep duration, stress, and anxiety levels of 52 participants were recorded using commercial fitness trackers and smartwatches. The participants who actively participated in their health monitoring made more informed decisions regarding their lifestyle changes.[23] Equally, a clinical trial that involved 221 participants used "standard intervention" with the commercial GalaxyWatch wearable and "enhanced intervention" integrating the GalaxyWatch with the Yonsei Health application.[24] The results demonstrated improvements in blood pressure and glycated haemoglobin levels in both intervention groups. However, participants in the "enhanced intervention group" demonstrated consistent increases in their step counts, leading to positive alterations in body weight, BMI figures and overall health, making them "healthier" than 'the standard intervention group. Another 2022 clinical intervention-based study investigated smart wearables' ability to improve blood pressure control in hypertensive patients, a disease affecting 1 in 3 adults.[25] Hypertensive patients were randomly assigned to either an intervention group or a control group, the intervention group used a digital bracelet (Sanjian Tech co, model H07) to monitor blood pressure continuously and provided a bespoke application with personalised health advice. This group demonstrated a significant improvement in blood pressure compared to the control group, who received standard care for hypertension management without technology.[26] Hence, the mere act of wearing a smart device is insufficient to foster health improvements; the wearer's active engagement and utilisation of smart wearables are crucial factors for achieving the desired outcomes in managing chronic diseases.

In addition to active user engagement, real-time monitoring of vital signs plays a pivotal role in managing chronic diseases, providing a valuable tool to detect variations that may indicate underlying health conditions.[27,28] A smart helmet, with electrodes positioned at the lower jaw, forehead and mastoids, facilitated comprehensive monitoring of cardiovascular and neural activity, serving as an effective means to analyse both physical and mental conditions. The authors validated its performance against traditional medical-grade ECG and EEG systems and proposed a multivariate R-peak detection algorithm, for accuracy in noisy real-life scenarios.[29] Another smart wearable, in the form of a "vest," extended its monitoring capabilities to include a wide range of vital signs such as electrocardiogram rate (ECG), respiratory rate, body temperature, and movement, offering insights into various health challenges. Its multi-parameter data acquisition system was designed using a microcontroller interfaced with wireless communication and global positioning system (GPS) modules, which enabled continuous monitoring of both vital signs and physical activity.[30] Hence, providing a more holistic view of an individual's health compared to the smart wearable helmet. Notably, effective monitoring of respiration, an additional health marker, contributes to the mitigation of chronic diseases. A non-invasive breath biochemistry smart wearable, designed to detect Hydrogen peroxide (H2O2), a biomarker relevant in respiratory conditions like Chronic Obstructive Pulmonary Disease (COPD), offered real-time detection with high sensitivity and specificity.[31] The real-time data captured provides valuable insights into user health and well-being. When integrated with urban environmental monitoring, a more comprehensive understanding of health challenges comes to fruition.

Indeed, many smart wearables suffer from cumbersome designs, and considering the inherent bustling nature of urban environments, the size of smart wearables plays a crucial role in their wider adoption. Tracking bracelets, smaller wearable sensors, have been determined as effective tools for remote health monitoring, as they can provide convenient and non-invasive means to monitor conditions like hypertension. This novel digital approach to aids preventative medicine, helping identify accumulative risk based on data collected, allowing proactive interventions.[32] However, they still hold some unreliability. Wireless wearable body area networks (WBANs) could drive innovation in the smaller digital field of smart wearables; their smaller, more accurate and more compact designs could result in greater comprehension of the correlation between human habits and disease.[33] WBAN technology has diverse applications and can integrate seamlessly into garments and other wearables.[34] However, the high cost of WBANs often translates into elevated consumer prices, which could further deter the wider adoption of smart wearables. Even though producing trustworthy, accurate data to provide more effective health interventions is crucial to maximising the benefits and impact on chronic diseases, the industry should prioritise the size and cost of smart wearables.

The potential of smart wearables to facilitate the reduction of chronic diseases is clear. However, to be considered accurate enough for populace use, such devices may require costly medical certification from the Medicines and Healthcare Products Regulatory Agency (MHRA).[35] A limited number of studies have explored using smart wearables to prevent chronic diseases in urbanised environments, highlighting a stark gap in the discourse. Further research in this area could provide valuable insights contributing to the development of innovative approaches to harness the potential of smart wearables in preventative health care.

Monitoring Environment Exposure

Despite the World Health Organisation's advocacy of healthy and sustainable cities, urban research considering relationships between urban features such as human movement, traffic, and urban densification presents a deficiency in government intervention practices within cities to assist healthier living.[5,36] Urban public open spaces (POS) drastically affect the mental and physical health of city residents. Participants wore a FrontRow wearable lifestyle camera, an *Empatica 4* medical wristband, and GPS tracker as a sensor package to assess stress responses when walking.[37] Machine learning algorithms presented POS features produced both positive and negative stress effects, depending on contextual factors. Some instances demonstrated certain plants heightened participant stress, especially when obstructing view, confirming a link between POS features and physiological stress. A reduced environmental stress response was also seen on a walked green route, compared to a grey route using handheld Airbeam sensors,[38] with participants relying more on natural features when they were present. Likewise, smart wristband ECG data from participants exposed to urban wetlands and "blue" spaces demonstrated a modulation increase in brain activity and attention in "blue" spaces.[39] A notable rise in mean heart rate and decrease in negative emotions was also observed, but only among participants with pre-existing high stress. There is a clear connection between living environments and negative stress, implying that urban environmental exposure can cause negative mental health effects.

Monitoring environmental exposure, known as the human exposome, is crucial to comprehend the effects on health, including perceived mood, well-being and observed comfort.[40] The *iButton Hygrochron,* a portable commercial sensor with 8 KB of data-log memory and data retrieval software, was worn to monitor a human-centric air temperature (TA) and relative humidity (RH). Daily reports of monitored variables and clustered calculated heat index data demonstrated common personal exposome profiles for each participant.[41] The study's limited collection of parameters restricted the characterisation of the sample, but additional parameters could provide valuable insights. For instance, a smart backpack tracked multiple parameters: wind velocity, air temperature, humidity, atmospheric pressure, solar radiation, and concentrations of particulate matter (PM1.0, PM2.5, and PM10) from a hyperlocal pedestrian perspective.[42] The system comprised a control unit and set of sensors, selected with environmental specification and power consumption in mind, housed on a backpack connected to Wi-Fi. The device offered a comprehensive view of urban spaces, aiding in the identification of environmental vulnerabilities and health risks, assisting urban planners to address the negative effects of urbanisation, and designing liveable cities. Given the influence that urban dwellers' actions and increased urbanisation have on exposure sources in metropolises, it is significantly important to accurately monitor the effects and causes of these exposures on human health.

Integrated sensor platforms can provide multi-parameter monitoring of complex urban exposures. A conceptualised care service architecture integrated with wearable, flexible sensors proposed to communicate with medical authorities, the design was said to enhance in-home health monitoring, exposure and health assessments.[43] Further integrated sensor platforms have been proposed to provide the opportunity for heat risk physiological assessments in research, clinical, and home settings to prevent chronic disease.[44] Sensor platforms portray the necessity to tackle the underlying factors contributing to declining urban health, presenting the promise to comprehend the source and effects of urban exposure. Considering an individual's lifelong exposures and their impact on health will play a significant role in determining future urban environments, influencing the activities of future urban dwellers.[45]

Indeed, increased human activities have already exacerbated the variability of environmental exposures.[46] A smart wearable backpack provides a pedestrian's view of urban environments. Synchronised measurements with established equipment presented accurate data collection across all sensor parameters, certifying accurate environment monitoring.[47] However, outdoor acoustics were not accounted for, which could have been valuable given the urban environment's noisy nature. Another mixed methods approach, a smart wearable study designed to monitor acoustic noise, temperature, particle number counts, and GPS data, portrayed high data parallels compared with traditional reference devices.[48] The large breadth of parameters collected portrays the challenge of documenting exposure data while individuals move through diverse urban settings, underscoring the need for rigorous performance evaluations before conducting studies. The trend leans toward studies involving multiple environmental parameters, emphasising the importance of identifying and quantifying the influence of various conditions on an individual's health.[49] Such assessments can guide the future selection of appropriate wearables for daily use, although more personalised conditions should be considered.[50]

Despite the evidence that various environmental characteristics have diverse impacts on human health, personal urban environmental exposure monitoring appears limited.[51] *PUFP C200*, a personal portable particle counter smart wearable was combined with the NEATVIBE wear TM (Noise Exposure, Activity-Time, and Vibration) wearable. Preliminary field test findings using two laboratory-validated tools that measure personal-scale exposures and noise with high spatiotemporal resolution. Indicated that smart wearables can effectively measure both noise and particulate matter pollution in parallel, providing precise personal exposure readings in different microenvironments.[52] While measuring personal environmental exposure accuracy is crucial, understanding its impact on human health should go further than the data collection and mitigate the effects of exposures like pollution.[53] There appears to be a gap in the literature as data collection is often the end goal without any corresponding action. To progress the proliferation and scalability of wearables and to successfully improve health, it appears necessary to encourage the joint monitoring and assessment of physiological, psychological and environmental exposure to ensure comprehensive and accurate comprehension of health.[54]

Assessing Urban Pollution

Many environmental features negatively impact human health; however, elevated air particulate matter directly impacts physiological functioning. Comparisons of three personal PM2.5 exposure monitors (one optical particle counter, two nephelometers) in various urban settings revealed inconsistent correlations between devices, suggesting potential fluctuations in air particulate matter even within closely related urban areas.[55] Wearable sensors, *e-TACT* and *BodyCAP Medical,* placed on the chest and armpit, investigated variations in skin and air temperature and the activity levels of urban and rural participants over 24 h.[56] Rural participants exhibited lower personal air temperatures than urban counterparts, but significant indoor temperature peaks occurred in both locations, indicating greater indoor fluctuations than outdoors. Additional personal pollutant data from a smart wearable with various sensors showed successful but potentially limited outcomes, not fully reflecting unpredictable urban conditions.[57] *Mypart,* a wearable sensor device, demonstrated viability in twenty everyday urban environments through a user trial.[58] A laser and photodiode were arranged orthogonally, with the laser above the photodiode. A fan drew air across the photodiode, which scattered the particles over the laser light onto the photodiode, generating a voltage signal. This signal was amplified and sampled by a microcontroller enabled particle detection. *Mypart* proved to be an effective, accurate, low-cost, and portable personal air monitoring system, influencing participants' behaviour to mitigate pollution effects. It is clear human behaviours have various effects on pollution severity, even within closely related urban areas.

Further, *Sniffer 4D* devices monitored PM1, PM2.5, and PM10, higher UPM levels during the "heating" season and revealed opposite spatial distribution characteristics of UPM quantities. Underscoring the impact not only of environmental temperature and humidity on UPM diffusion but also the impact of human behaviours.[59] Another human behaviour, transportation, significantly contributes to UPM, evidenced by low-cost wearable sensors designed using existing open-source hardware designs that detect UPM presence through dynamic light scattering technique modes.[60] The wearable measured exposure during various transport, exhibiting buses with the highest PM exposure, followed by subway use, cycling, and walking. Indeed, smart wearables can affect such human behaviours. The Sharp GP2Y1010AU0F wearable, worn by students during their daily commute, revealed a significant increase in environmental awareness and more sustainable behaviours over several weeks, with data logged through a microcontroller.[61] However, further results have also indicated that individuals who consistently spend more time outdoors in cities or areas with high traffic congestion face an elevated risk of particulate matter exposure.[62] There is a need for advanced personal exposure assessments using smart wearables to alter human behaviours and educate those living in cities about the threats they face regarding pollution.

The prospect of improving personal exposure assessment was presented by the *Canarin Project*, a low-cost personal air pollution smart mask offering the possibility of enhanced vital signs, pollution level, and physical activity monitoring[63] The design proposed that electroencephalography (EEG) and electrocardiography (ECG) sensors could measure the brain and heart electrical activity. A week-long trial with 32 participants demonstrated the system's ability to provide mostly reliable measurements of nitrogen dioxide, ozone, and particulate matter.[64] However, the limited duration and small participant group reduce the generalisability of the findings, underscoring the variability of air pollution exposure risks despite the ability of wearable sensors to provide some accurate data. A more integrated textile sensor design provided more personal NO_2 ambient air data, with Graphene oxide (GO) and molybdenum disulphide (MoS_2), e-textile sensors fabricated by a modified dip-coating method embedded in a nylon fabric.[65] Utilising unencapsulated two-dimensional materials, the washable e-textile maintained a high sensitivity and selectivity for NO_2 detection, even in the presence of interfering gases, presenting smart garments over accessories can provide more accurate data due to their more expansive wearability. Indeed, air quality insights using data from smart wearables can empower individuals to make informed decisions about their pollutant exposure. Consequently, the development of this technology should involve and cater to both the needs of the public and the individual.[66]

Outdoor Physical Activity Assistance

A randomised crossover study of 115 healthy participants wearing a *"Sense wear"* band and a *microlith* examined if the effects of black carbon inhalation would reverse physical activity's beneficial impacts on lung function.[67] Mixed regression models analysed forced expiratory volume in the first second (FEV1), forced vital capacity (FVC), peak expiratory flow and forced expiratory flow (FEF). The findings suggest that exposure to black carbon negates the beneficial effects of physical activity on lung function and highlights the importance of minimising exposure to pollutants in urban environments. Increasing evidence links personal environmental features to air pollution severity. The *SHE* project assessed physiological responses in combination with personal environment atmospheric and traffic pollution particle data. Participants wore a wearable heart and respiratory rate monitor, engaging in outdoor physical activity along a "green" and "red" route.[68] Environmental sensor nodes placed along the exercise routes detected higher concentrations of pollutants on the red route, suggesting that urban parks and green spaces can reduce the concentrations of most pollutants. Hence, smart wearables, with the ability to monitor real-time air pollutant levels, can provide users with feedback on the times and routes to engage in outdoor physical activity, if any.

Indeed, engaging in regular physical activity enhances the overall quality of life and is known to contribute to premature mortality prevention.[69] However, during urban outdoor physical activity, higher ventilation rates result in an increased inhalation dose of air pollutants. Consequently, outdoor urban exercise exacerbates the likelihood of respiratory diseases among urban residents, as exposure to pollutants intensifies cardiovascular and respiratory system impairments.[70] A non-invasive, low-energy, and cost-effective monitoring sock was proposed to monitor heart rate, oxygen saturation, sweat, body temperature, physical activity, and pressure.[71] The system generated a comprehensive health overview of the user through an algorithm-based data analysis, including any potential negative effects arising from personal external exposures. Integrating such advanced wearable technologies provides a favourable approach to monitoring and mitigating the impacts of environmental exposures on individual health and well-being.

Indeed, urban outdoor physical activity faces barriers beyond pollution. Despite walking being a common low to moderate-intensity exercise for urban dwellers, barriers to walkability exist. A smart wearable sensor recorded the gait process of 64 participants, revealing differing behavioural responses to environmental barriers.[72] While the study's small sample size and limited data collection areas may impact reliability, smart wearables show potential in assessing environmental barriers, particularly in specific conditions. Sedentary behaviour in urban environments poses cardiovascular risks, addressed by smart wearable IoT prototypes integrated into garments for real-time assessment.[73] This experimental protocol for the elderly demonstrated accurate detection of various activities with a "95.00% ± 2.11%" accuracy. However, the device's efficacy may vary with different activities and a wider population. While smart wearable systems hold promise for cardiovascular risk assessment and activity encouragement, current research has primarily focused on the elderly.

Engaging in regular physical activity is crucial for maintaining good health, and outdoor exercise offers more significant physiological benefits than indoor exercise. Smart wearables have proven effective in monitoring both environmental and physiological factors during exercise, but there is a shortage of relevant studies. As a result, it is difficult to obtain a complete understanding of the safeguarding capabilities of smart wearables in this area.

New developments in wearable technologies.—Smart wearable sensors hold great potential to empower tailored mental and physical health monitoring, enabling predictive health analysis and timely interventions. Technological developments are occurring at rapid rates, advances in flexible electronics, materials science, and electrochemistry have spurred the development of wearable biosensors that enable the continuous non-invasive assessment of health.[74]

As sweat contains abundant biochemical information, wearable sweat sensors can better comprehend the biochemical processes that govern our health, enabling precision medicine through personalised monitoring.[75,76] Many sweat sensors are potentiometric sensors based on ion-selective electrodes (ISEs) that convert ionic signals to electric potentials in a non-destructive way.[77] Such electrochemical sensors comprise a sensing electrode reformed with a target-sensitive component and a reference electrode maintaining a stable potential in varying solutions like sweat. However, studies validating wearable sweat-sensing need to be conducted further to improve the contextualisation of sweat biomarkers concerning health conditions.[78] The use of personalised real-time health data collected from sweat sensors can push smart wearable sensors into mainstream use.

Another emerging smart wearable sensor that has gained significant attention is microneedle sensors, which intend to combine sensing technologies and micro-needles for biomolecule investigation to advance point-of-care (POC) health monitoring.[79] Microneedle sensors consist of a micron-scale needle collection, enabling a shallow penetration depth to provide a minimally invasive method to puncture the skin near-painless.[80,81] The microstructure of the micro-needles is significant in the extraction of bodily fluids. Current microneedle wearables can be classified into solid, hollow, porous, and coated categories, each with various advances and drawbacks.[82] Despite their inherent complex design, microneedle wearable sensors have been recently applied as powerful wearable sensor platforms to detect clinically significant substances and monitor biomarkers or ingested medicines.[83,84] Integrating advanced biosensors into wearables presents a promising avenue for the future of smart wearable sensors, whose capabilities extend beyond simple "sensing."

Challenges of using smart wearables among users.—Despite the growing popularity of smart devices, concerns have been raised regarding their wearability. When smart wearables take the form of garments, washing needs arise to minimise bacterial growth and contamination, especially for health-related wearables.[85] However, incorporating electronic components garments, including wires, circuit boards, and batteries, presents challenges for the washing process, as these components cannot be washed without being damaged. One potential solution is to design smart garments with removable electronic components.[86] However, this approach introduces its own set of challenges, as it would require consumers to remove the components before washing. This could raise regulatory concerns related to the handling of powerful electronics and cause concerns regarding their correct placement back into the garment.[87] Alternatively, smart wearable wristbands, headbands, or ankle bands have limited washability issues, as these devices are primarily wipeable. However, it should be noted that diverging from a garment limits the sensor capabilities as fewer unobtrusive body positions can be worn.

The fashion industry operates in a highly dynamic and rapidly evolving environment, where garments and accessories are constantly designed, produced, and discarded with each season, resulting in significantly short garment lifecycles.[88] This poses challenges for smart wearables, as they are designed with long life cycles due to their higher manufacturing costs. Consequently, smart wearables cannot adhere to rapidly evolving fashion trends, which may deter fashion-conscious consumers from purchasing smart wearables. Indeed, a "classic" and timeless design suits smart wearables, emphasising simplicity for easy incorporation into a large consumer-based clothing repertoire.[89] However, such an approach may not resonate with mass markets that value dressing according to their style and preferences. An example of a successful smart wearable brand is Fitbit, which offers personalised devices with easily removable straps, allowing users to adapt the device to any occasion.[90] For smart wearables to be accepted, they should adopt similar product models, incorporating removable electronic components that can be attached to different garments and accessories, enabling seamless integration into users' wardrobes.

User acceptance of smart wearables extends beyond their physical aesthetic. Data storage, often connected to big data, is another essential concern that can significantly deter the adoption of smart wearables. Big Data refers to large data sets that are collected and analysed to reveal patterns and trends.[91] In smart wearables, the data relates to human behaviour and mass-scale interactions.[92] As consumers have become more conscious of the implications of sharing their data and trading privacy for technological advancements, data ownership concerns have emerged as a substantial barrier. For instance, Google's search history data is tracked, owned, and stored by Google rather than the individual searcher. However, Google does not claim ownership over the content generated by users within their software, such as text or images.[93] Indeed, the issue of data ownership and control becomes particularly pertinent with smart wearables. For instance, the e-TACT sensor discussed above was designed to collect vital signs and microenvironmental data from users wearing the device.[56] While this data collection can offer valuable insights into individual health and well-being, typically, the wearer relinquishes ownership and control over their data. Wearers may worry about how their data will be stored, shared, and potentially monetised by the smart wearable company. Addressing these complex data ownership issues will be vital to protect user privacy and rights, foster trust and encourage wider adoption of smart wearables.

Indeed, using inappropriate data transfer mechanisms can result in data leakage, posing a risk to the rights and freedoms of individuals.[94] Within the context of smart wearable data, this could lead to the theft of personal health data. In artificial intelligence (AI), where vast amounts of data are processed and analysed, the risk of data leakage and corruption is particularly pronounced.[95] AI systems rely heavily on data transfer mechanisms to function effectively, making them vulnerable to potential security breaches if appropriate measures are not in place. All forms of data storage are susceptible to corruption, which highlights the importance of robust data protection measures.

Moreover, interdisciplinary collaboration between data scientists, researchers, engineers and designers is crucial for addressing data security concerns and advancing the physical development of smart wearable devices.[96] Effective collaboration across separate fields is essential to ensure smart wearables' safe and successful evolution. Such collaborations can present challenges and complexities that must be negotiated between collaborators and supported by adequate resources, funding, and infrastructure to facilitate research, development, and testing of smart wearables.

Scope.—With the introduction of smart cities, smart wearables have the potential for comprehensive integration within the urban environment. This expanded scope transcends simple data collection and enables technological interventions to filter into various aspects of urban dwellers' lives. Smart cities and smart wearables could become intelligent enough to provide urbanites with tailored sustainable development and intelligent lifestyle solutions.[97] For instance, artificial intelligence (AI) is becoming a progressive element of many industries, with a scope to become constant assistance across the globe. AI models could be integrated into homes, work offices and outdoor spaces and connect to the smart devices' urbanites wear. The city's AI models could process vital sign data from the smart wearables to provide care, assistance and general living advice tailored to every urbanite's unique needs. However, as cities are intricate ecological networks, AI models will need to account for the different needs of the city.[98] Hence, they have a requirement to respond to consistent environmental changes.[99]

It must be acknowledged that smart wearables could present transhuman possibilities. The distinction between the wearer and the worn smart technology could become increasingly indistinguishable, transforming the "wearer" into something beyond human. Brain-computer interfaces (BCI), enable individuals to send information directly from their brains to computers, sending commands without moving.[100] A publicised BCI 2009 presented a finger and replaced it with a USB drive, enabling the wearer or "host" to store photos, videos, and other useful content on their "finger."[101] Recently, BCI's have been perceived as promising approaches for rehabilitation, like for post-stroke patients. However, new evaluation criteria need to be established, with more objective biomechanical assessments to establish BCI's safe application.[102] BCI's could also to enhance metacognitive monitoring. A BCI-VR was able to evaluate the emotional responses of designers to their work, providing real-time, visual biofeedback of the responses.[103] Although only providing a proof-of-concept this study offer promise with BCI's, presenting their potential future scope into several different health comprehending and enhancing areas.

BCI's and other emerging transhuman "wearable" technology demonstrate the potential of smart wearables to expand the human concept. Such developments present unique challenges, especially concerning ethical considerations. They are perpetuating the essential responsibility to instil the development of smart wearables with a sense of user input and conscientiousness.

Conclusions

Smart wearables offer promising solutions to improve the lifestyles and health of urbanites. This review has investigated the potential of smart wearables to enhance the health and lifestyles of urban dwellers by examining the existing literature. The findings demonstrate the significant impact that smart wearables can have on improving health outcomes and empowering individuals to take control of their well-being. Wearables inherently enhance health but serve as monitoring tools that allow users to make informed choices and take proactive steps towards health improvement based on the provided data. Considering the influence of urban dwellers' behaviours on their urban surroundings and personal health, adopting smart wearables could catalyse and encourage positive health-benefiting behaviours. By actively using smart wearables, individuals can cultivate positive lifestyle habits that can significantly enhance their health outcomes and, by extension, the condition of their urban dwellings. However, a one-size-fits-all approach to smart wearables is less practical, as individuals have specific needs. Personalisation is vital to optimising the health benefits of smart wearable devices. The wearer's active engagement and utilisation of smart wearables are crucial for achieving positive outcomes.

Nevertheless, there are potential concerns regarding smart wearable technology, wearability, user acceptance, data privacy, and high initial costs. These challenges need to be addressed for the technology to reach its potential. Further research in this area could provide valuable insights that contribute to developing innovative approaches to harness the potential of smart wearables to mitigate the challenges regarding the technology. With continued development, smart wearables have the potential to redefine urban health, connecting humans to their surroundings and technology.

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