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Perspective

General Conceptual Framework of Future Wearables in Healthcare: Unified, Unique, Ubiquitous, and Unobtrusive (U4) for Customized Quantified Output

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Abstract: We concentrate on the importance and future conceptual development of wearable devices as the major means of personalized healthcare. We discuss and address the role of wearables in the new era of healthcare in proactive medicine. This work addresses the behavioral, environmental, physiological, and psychological parameters as the most effective domains in personalized healthcare, and the wearables are categorized according to the range of measurements. The importance of multi-parameter, multi-domain monitoring and the respective interactions are further discussed and the generation of wearables based on the number of monitoring area(s) is consequently formulated.

Keywords: wearable devices; healthcare monitoring; future generation of wearables; ubiquitous monitoring

1. Highlights and Key Messages

The key messages from this study are:

- Wearables need to simultaneously monitor environmental, behavioral, physiological, and psychological parameters;
- Wearable design, features, and functionalities should bridge users, healthcare professionals, and caregivers;
- Wearables should deliver customized quantified output by linking a customized user profile and (library-based) disease specifications;
- Unified, unique, ubiquitous, and unobtrusive (U4) are proposed as the criteria for the future generation of wearables;
- Wearables should address the concerns of users and healthcare professionals (physicians) according to cost-effective, convenient, continuous, and complete (C4) and anywhere, anything, anytime, and anyone (A4), respectively.

2. Definition of Wearables, Applications, and Our Contributions

Wearable technology is an emerging trend that integrates electronics into daily life and tracks a wide range of activities and elements that fit into a person's lifestyle [1]. Current breakthroughs in semiconductors, communication protocols, and sensors technologies have propelled the wearable market, which was valued at USD $27.91 billion in 2019 and is forecast to increase to USD $74.03 billion by 2025 [2]. Wearable devices can be worn on any part of the body (e.g., wrist, arm, head, neck, foot, or waist) enabling data exchange. They have been applied in various fields from safety [3], navigation [4], fitness [5], and sport [6] to healthcare [7], entertainment [8], and industry [9], and they have been introduced as important players in the Internet of Things (IoT) era [10]. With the application of wearable technology, the future might be quicker, healthier, safer, and more entertaining. Overall, the healthcare sector might be where wearables have the greatest potential [11]. Healthcare experts think that a combination of medical systems, technologies, and software development supported by consistent data exchange (known as interoperability) and analysis are the key points to the transition from intermittent patient monitoring to real-time continuous monitoring. Recently, several factors, such as decreasing the price, shrinking sensor size, and providing easy access to open-source application programming interfaces (APIs), frameworks, and libraries, have enhanced the potential of the wearables in becoming the method used for monitoring people's health. However, wearability, convenience, accuracy, reliability, interpolation, interpretation, and resolution pose serious barriers [12]. The application of wearable technology is determined by the target design. Some families of wearables have been designed for monitoring, prediction, and prevention of the user [13]. Some target the management of users and diseases [14], and others facilitates and influences decision-making [15]. The efficiency of wearables was investigated in some studies for short clinical trials, and the promising results indicated the contributions of wearables to the quality of monitoring and the services provided by medical centers with supporting informative health status data and efficient end-to-end communication [14]. In this work, we concentrated on the first group of target wearables; thus, we addressed three aspects of their importance and usage in healthcare:

- Healthcare systems are upgraded from reactive to proactive

  People who feel pain or something abnormal will go to see a doctor. This is the usual method for most people experiencing potential health risks, which is known as reactive. Using wearables motivates the user and supports a potential proactive approach to healthcare by long-term monitoring and detecting emergencies [16]. The proactive approach might be beneficial because health issues can be detected at an early stage before developing into a more serious issue that could have negative health consequences. In particular, using wearables is highly recommended to vulnerable patients with specific weaknesses [17].

- Users are informed, engaged, and motivated

  Measurement, collection, and real-time data observation are currently supported by several wearables. Wearables can detect the abnormalities and inform the user by tracking the daily values, thresholds, boundaries, and variations in intended parameters in real time. This is why some of the insurance companies have already encouraged the use of wearables [18]. The data and the created pattern and figures can indicate the user's lifestyle and motivate them to change and improve, if necessary, to enhance the general quality of health/life [5].

- Healthcare providers are benefited

  The healthcare system includes another party in addition to patients: physicians and professional caregivers also might benefit from big data collection and prolonged monitoring to obtain a more accurate diagnosis and to help with decision-making. Using wearables may also reduce the cost that is imposed on medical systems [19]. Statistics show that 20% of all healthcare costs result from a lack of sufficient physical activity and exercise, sleep disorders, and addiction to drugs, alcohol, and tobacco [20].

Given the points stated above, both users and physicians, as well as all parties included in the healthcare system, benefit from wider application of wearables [21–24]. In addition, caregivers can be engaged in the system for providing assistance in case of emergencies that are detected by the wearable. To achieve this, the demands and requirements of the involved parties (users and physicians) must be strictly considered and fulfilled.

To address the issues and the current aim, the World Health Organization (WHO), as the worldwide healthcare reference, has identified the following four effective areas that need to be monitored to protect human health: environmental, behavioral (physical activities), physiological, and psychological [25]. We briefly mention the most important parameters of these areas, but the list can be further extended. In the behavioral area, various physical activities, including mobility, step counting, user walking speed, etc., are important [26]. The physiological area may consist of vital signs as well as skin conductance [27]. Toxic and hazardous gas pollutants, ultraviolet (UV) radiation, sound level, air pressure, temperature, and humidity are the effective parameters in the environmental area [28]. Finally, stress and strain can be the most valuable parameters in the psychological aspect [29]. These four areas are interwoven because each parameter in a domain might be influenced by the parameter(s) in the other domains; thus, extensive data measurement, collection, fusion, and integration are necessary to calculate the mutual impact among different parameters and to assign a weight to each. This means that adequate decision-making and identification of a medical diagnosis are the functions of proper algorithm development, which require effective data, collection, fusion, and integration, which are impacted by continuous monitoring [30].

However, the recommendation to use wearable(s) is based on conditions that satisfy several criteria. To date, the majority of available wearables have been designed using a familiar structure that measures specific parameters for some predefined diseases without considering the user's profile (i.e., personalized medicine) [31,32]. In addition to the lack of comprehensive monitoring, wearability, prolonged monitoring, and cost of wearables are the other barriers to advances in wearables applications [33]. Such devices are delivering some raw data. However, analysis and decision-making is considering historical medical records.

3. Generation of Wearables: Current Status

To discuss the current status of wearables, we considered and categorized wearables from the perspective of monitoring in healthcare. These include behavioral, physiological, environmental, and psychological domains. As each domain may include several parameters, the criterion is the domain rather than the parameter. We identify each domain by clustering the parameters, highlighting the borders, and labeling the current wearables with a generation. We define G_n, where G is the generation and n is the number of monitoring domains for each wearable.

Thus, wearables labeled G_1 only measure one domain of the four domains discussed above. This domain could be either behavioral, environmental, physiological, or psychological, but not two of them simultaneously. Each generation might have several versions, considering the features, characteristics, and optimization. As examples, in this definition, wearables that measure either three-dimensional (3D) motion tracking (physical activity) via inertial measurement units (IMUs) [34], air pollutants (environmental) [35], vital signs (physiological) [36], and emotion and stress (psychological) are widely used and represent the first generation of wearables (G_1) [37]. However, version of the generation varies from one wearable to another depending on the wearability, computation methodology, and processing, which is not the focus here.

The integration of micro-electromechanical systems (MEMS) into IMUs has enabled miniaturization along with high performance and low power consumption for precise and high-resolution physical activity measurement. This miniaturization has enabled the sensor fusion of IMUs in each of the other domains, which advanced the wearables from single-domain monitoring to double-domain monitoring (G_2) [38].

Due to miniaturization of IMUs, the behavioral domain is a consistent aspect of third-generation wearables. IMUs are often integrated with any of the two other domains. Behavioral, physiological, and psychological parameters are often user/patient-controlled and are considered the interactive internal parameters that cause mutual impact and parameter interactions. As the third generation of wearables is restricted to monitoring only three domains, in the majority of the cases, the behavioral, physiological, and psychological domains are combined. However, any combination of behavioral, physiological, psychological, and environmental domains consisting of only three domains is known as G_3 [39].

The environmental parameters are considered to be externally-imposed influential factors that affect the other three domains but basically are not influenced by the other domains. Therefore, due to the interaction of the environmental with the others domains, the simultaneous investigation of impact of environmental, behavioral, physiological, and psychological domains on the human health appears to be necessary.

The WHO refers to environmental pollutants as causing a noticeable mortality rate [40]. Many respiratory diseases (e.g., chronic obstructive pulmonary disease (COPD)) have a higher incidence because of exposure to air pollutants [41,42]. Additionally, air pollutants increase stress, strain, and the risk of heart failure in particularly vulnerable patients [43–45]. However, given the variability of sensors for measuring environmental factors (high power consumption, frequent calibration, and large scale), they are mostly ignored [20,46,47].

By now, comprehensive healthcare monitoring necessitates simultaneous measurement of all four domains. Consequently, acquiring reliable and precise physiological and psychological signals without considering the environmental domain is impossible.

In summary, rethinking and redesigning the development of wearables is a fundamental need for improving their performance and creating accurate diagnosis. Here, we categorize the wearables according to the domain and their combinations, demonstrating the future direction of wearables and propose taking a new route to advance wearable methodologies, approaches, and technologies into an ideal future generation. However, comprehensive monitoring is not the only concern, although the major one. Convenience and prolonged monitoring, plus reliability and cost-effectiveness, are the serious concerns in the field that need to be considered.

4. Future Generation of Wearable Systems (G_4): Challenges and Opportunities

During technological evolution, demand is the influencing factor that creates requirements and propels science forward. In personalized healthcare, demands are created by physicians and users. Therefore, the triangle of demands, requirements, and technologies are closed with simultaneous consideration of both groups (physicians and users).

A wearable has merit in healthcare when it satisfies the requirements of physicians and users. Designing a successful wearable is the function of user–physician compromise. Under such conditions, the medical and technical demands are complemented by the expectation of users to encourage wearing and to establish active communication with healthcare providers. Conceptually, user demands can be different from those of healthcare providers [48].

A user will wear a device when it will not interfere with her/his daily routine (convenience and continuous) [49] and delivers significant information that is interpreted by the user as an indicator of her/his general health status (complete). Additionally, from an economic perspective, the wearable must be affordable and worth purchasing (cost-effective) [50]. Thus, we introduce C4 as the criteria for a qualified wearable to represent the users' demands, which include: cost-effective, convenient, continuous, and complete [7].

However, looking at the future generation of wearables from a physician viewpoint, demands are increasing, consisting of reliability and accuracy of measurements, critical setup parameters and mutual interaction, efficient data analysis, and investigation. Physicians expect an interactive device to measure a wide range of parameters during a long period, that it can be used for several users without hardware changes and restrictions, but that it is easily adjustable and configurable to the patient/user depending on her/his current status [51]. Anywhere, anything, anytime, and anyone are the A4 demands important to physicians. We note that A4 and C4 also contain mutual interests [52].

According to the A4 and C4 criteria, we suggest "quantified customized output: unified, unique, ubiquitous, and unobtrusive (U4)" for future-generation wearables that constitute G_4 (Figure 1).

We provide a strict definition of U4 as:

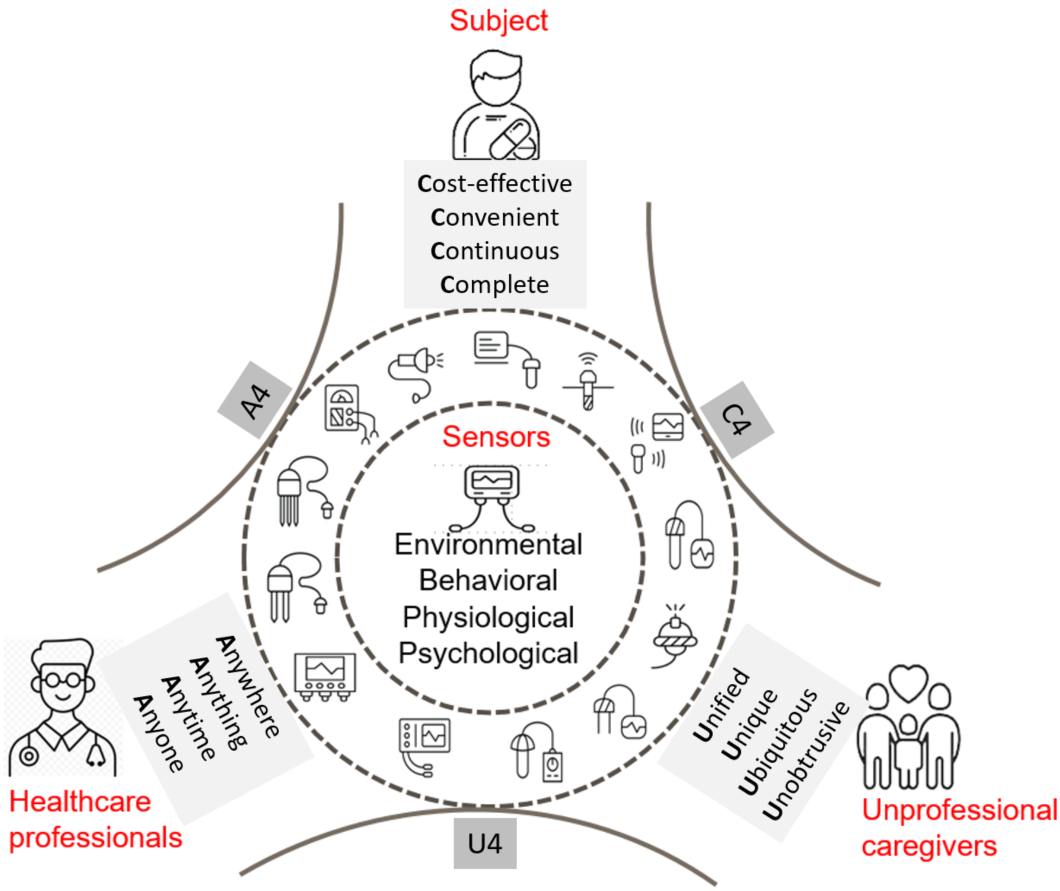

Figure 1. Conceptual framework for future wearables.

- Unified: the sensor addresses data fusion and mutual interactive effects.
- Unique: the output value that is only significant with respect to the user (customized profile) and the particular study (library-based).
- Ubiquitous: the potential of the device to measure all four domains under different conditions.
- Unobtrusive: address the concern of the inconvenience of monitoring using wearables.

Having a quantifiable customized output addresses and links the mutual interaction between the customized profile of the user and the disease profile. This feature is supported by comprehensive healthcare monitoring as the fundamental theory of G_4 wearables. To deliver a quantified customized output, data fusion, integration, interaction, along with assigning weights to interactive elements, and modeling the input/output route of data are essential. Consequently, developing the patterns and algorithms of collected data from these domains is necessary. The output is absolute (rather than relative) and informative to the user with respect to the disease, providing an early digitized warning in abnormalities.

The following example provides perspective with respect to the approach. The exposure to air pollutants (environmental) can significantly reduce physical activity (behavioral) and result in a malfunction of the patient's respiratory system and heart (physiological), which consequently may lead to stress development (psychological). However, in this particular example, the impact of pollutants on the exposed user is a function of the user's profile, which varies among users [53]. Thus, we suggest user profile customization via library division. This is accomplished by observation of the user for a limited period to carefully specify the user's profile and characteristics. To create an efficient user-based profile, the user's general information consists of parameters such as age, sex, height, weight (which should be set manually), historical medical records, and lifestyle (e.g., being a smoker, which should be obtained via observation); the living location would also be helpful because of atmospheric conditions. However, profile customization includes personalized data and transmission of the physiological/psychological data, which raises security concerns and creates the potential risk of endangering personal privacy [10,54,55]. Although a number of approaches have been developed and studied for data security and privacy protection [56–59], the more recent and advanced approaches concentrate on data sharing and security via blockchain [60,61].

The library addresses all specifications of a disease and respective thresholds. The library is loaded and the device is configured based on the aim of disease-oriented monitoring or general data collection that tracks the general daily health status. Library-based monitoring is a flexible solution to allow interactive communication between physicians and users via the wearable to set up the target parameters for diseases (disease orientation) [62]. The library is the collection of all related and intended diseases with their characteristics, profiles, and thresholds. The link between the library and the user profile significantly improves weighting the effect of a particular parameter and enhances the accuracy of the quantified output and consequently contributes to decision making.

Software modeling and development should be supported with an appropriate hardware design. As a result of the diversity of sensors and the nature of data, the localization and positioning of the respective sensors are challenging. We think that future wearables, even with comprehensive monitoring, can be unobtrusive and miniaturized. The approach we suggest is based on distributed sensors and centralized processing. In this manuscript, distributed indicates the sensors in different layers, which we call a "tray of sensors". The traditional approaches are basically implemented on the "XY" (2D) plane. According to the 2D approach, additional sensors impose further spaces and expand the dimension. We propose a 3D cube holding several trays of sensors with multiple physical layers on top of each other, each consisting of a sensor domain. The inner and outer surfaces of this 3D cube will be enriched with sensors. In the 3D cube, we suggest breaking down the 2D plane into smaller pieces. Increasing the number of layers allows the designer to add sensors. This comes at the cost of a slight height expansion of the wearable, which is tolerable. We considered board-to-board connectors in the form of male/female in mm scale to support the signaling between sensors and processing unit. A significant aspect of this approach is modularity, which is provided with such connectors.

Measuring physiological and psychological parameters requires direct contact with the body, whereas the environmental sensors more often need to be freely exposed to air, and the IMUs may be located arbitrarily anywhere on a wearable. This physical hardware approach is supported by bidirectional data transmission to enable a modular approach with replaceable trays that meaningfully contribute to the data setup, library-based, and customized user-based features according to the healthcare provider's requirement for investigation.

5. Conclusions

Our conceptual approach delivers quantifiable personalized output to significantly indicate the current health status of a user in future generations of wearables. Thus, the approach aims to close the gap between the subject, healthcare professional, and unprofessional caregiver perspectives, to establish interactive communication, motivate the patients using wearables, and to facilitate precise and seamless decision-making to accelerate the evolution of wearables.

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