How Wearable Computing Is Shaping Digital Health

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Wearable computing enables more personalized healthcare through a distributed information sharing model that puts patients and users rather than providers, insurers, and other industry stakeholders at the center. It also fosters the creation of new health knowledge and more effective prevention and treatment techniques by integrating vital-sign data, health-related behavioral data, and environmental-exposure data with clinical and genetic data. Realizing the promise of wearables and digital health, however, will require multiple parallel technological advances.

Wearable computing has introduced new approaches, more efficient processes, and innovative products in entertainment, sports, industrial logistics, and many other areas. However, no other field is anticipating and integrating wearable technology so broadly as healthcare, with interests ranging from well-being and disease prevention to chronic patient care and cross-cutting all medical disciplines.

Wearable computing researchers have foreseen numerous healthcare applications for at least two decades. Within the past several years, however, medical professionals and engineers have started integrating wearable technology in diagnosis and care processes, validating their effectiveness with patients in observational studies[1] and even randomized controlled trials.[2] A leading example is the continuous glucose monitor, which enables diabetic patients to self-monitor blood glucose levels and learn from the measurements about their body functions, leading to advanced self-management and treatment procedures.[3] However, the variety of wearable technologies and applications in healthcare stretches far beyond glucose monitoring. Medical journals now regularly publish articles with wearables at the center of their methodology and some, such as the *Journal of Medical Internet Research*, dedicate space to such technology.

What drives wearable health technology development? Although cost is a primary factor, wearable computing offers more than greater efficiency in clinical processes and the ability to monitor vital parameters—it promises to assume a unique role in maintaining health, improving patient conditions, and extending quality life-years.

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THE CHANGING INFORMATION LANDSCAPE

To understand wearable technology's future role in medicine, it is important to reflect on healthcare's ongoing transformation.

As Figure 1 shows in simplified form, patient information has traditionally been stored and processed by healthcare practitioners, hospitals, specialty clinics, insurers, and other industry stakeholders independently. These organizations manage all medical processes—from prevention and diagnosis to intervention, recovery, and chronic disease care. The concentration of more and more data and knowledge in centralized IT systems has invariably led to the systems and staff being overwhelmed with requests and tasks. It is important to note that the well-known concept of *patient-centered care*, wherein each patient's individual values and health outcomes guide clinical and care decisions, is compatible with and widely implemented even in centralized information systems.

The current system's structure can contribute to soaring costs: Across the EU, healthcare spending now accounts for nearly 10 percent of gross domestic product on average.[4]

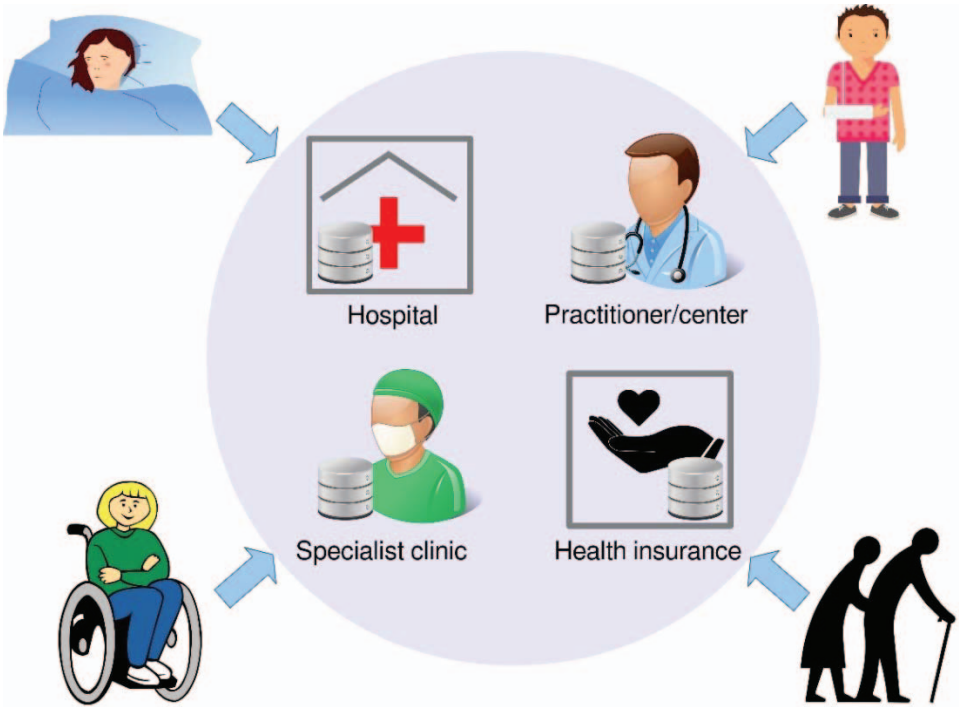

Figure 1. Patient information has traditionally been concentrated in the hands of healthcare providers and insurers.

Also adding to healthcare costs is the unmet need for medical care, in particular for low-income groups, resulting in more patients attending hospital emergency departments. In Germany, for example, about 25 percent of patients who visited an emergency department between 2011 and 2013 might not have required emergency care.[5] In addition, even though treatment effectiveness is continually improving, chronic and noncommunicable diseases are on the rise because of our aging society. Thus, we need concerted efforts and planning for prevention and long-term care with cost-effective health services for years to come.

The advance of wearable technology has motivated healthcare professionals to look outside the office or clinic to help identify health risks, monitor disease progress, and provide treatment or advice. For the first time, relevant data can be acquired independently from a controlled clinical setting. Continuous monitoring over days, months, or even years is feasible. Simultaneously, users are becoming more knowledgeable about health topics and the information collected by

wearable devices, which extends far beyond Quantified Self (lifelogging) nerds. Leveraging Internet resources and social networks, users are self-interpreting their data and sharing and discussing their findings with others. Consequently, new well-being and patient interest groups are emerging as citizen science communities.

As detailed in the previous Wearable Computing department,[6] wearables are moving beyond traditional form factors such as smartphones and smart watches. Sensors in smart on-body accessories, smart cloths, and smart body patches can gather novel types of health data and provide interventions such as on-demand drug release. Smart implants for nonsevere medical conditions are a likely future addition.

As Figure 2 shows, wearables are leading to a new health information model that puts users and patients at the center of a distributed information sharing system. With hospitals and practitioners no longer the sole or even the main data generators, wearables will assume greater importance in forging new insights and developing more efficient processes. Compared to traditional systems, wearables will generate data at higher velocity (as measurements are continuous) and at higher volume (due to wearables' rising utility), and such data will be more varied because of the numerous types of sensors and interactions.

Figure 2. The generation of big data through wearable and mobile health technology is leading to the emergence of a distributed information sharing system in which all industry stakeholders—including providers, promoters, insurers, and device manufacturers—participate in storing, providing, and mining health data.

With data virtualization, healthcare data is no longer centralized in a few places and only accessible through a handful of gatekeepers. Instead, providers, promoters, insurers, and device manufacturers are now storing, providing, and mining user and patient health data.[7]

At least initially independent of the wearables development, many countries have launched efforts to increase collaboration among different health industry stakeholders. In 2015, for example, the Obama administration launched the Precision Medicine Initiative (now All of Us) to facilitate information sharing among patients, researchers, and providers to improve healthcare delivery.[8] Germany recently created a €150 million fund for medical informatics research to improve data management and sharing,[9] primarily in hospital networks.

Clearly, data management, mining, and interpretation require proper access and control mechanisms, as well as federation, curation, and compatibility standards for databases and the integration of electronic medical and patient records. Wearable technology will extend and diversify these challenges. In addition, as patients obtain more control over health data, they also must assume greater responsibility for managing it.

INTEGRATING WEARABLE COMPUTING WITH DIGITAL HEALTH

Digital health refers to the convergence of various information technologies to maximize healthcare effectiveness, including data management (eHealth), mobile devices and apps (mHealth, wireless health), and remote patient management (connected health, telemedicine). Various governments have launched digital health programs through their main health agencies, including the UK's National Health Service[10] and the US Food and Drug Administration.[11] Market studies highlight the many benefits of digital health including higher productivity, better clinical outcomes, and a more satisfying patient experience.[12] Researchers also see digital health as a major driver for personalized medicine.

Wearable computing is shaping digital health in multiple ways.

Preventive Medicine

A central goal of digital health is to prevent disease and identify its onset at the earliest possible stage. Wearables have the potential to identify many early physiological and behavioral markers of chronic diseases. With this in view, the European Innovative Medicines Initiative (www.imi.europa.eu/about-imi) brings together pharmaceutical companies and researchers to investigate how wearable and mobile technology could be used to diagnose autism, diabetes, depression, and Alzheimer's disease sooner. Wearables are already used to promote healthy behavior through self-tracking and gaming approaches. Many other health promotion opportunities are sure to emerge with new wearable technologies.

Clinical Support

Capturing complex clinical processes using digital data management models could improve healthcare treatment and decrease errors. Researchers have demonstrated that wearable technology can support this effort by, for example, dynamically providing relevant information in ward rounds or detecting mistakes in operating theaters.[13] In furtherance of this goal, my colleagues and I developed pattern analysis methods to interpret unsupervised behavior and estimate independence in daily activities of poststroke patients measured using body-worn inertial sensors.[14] Support for clinical processes, along with online and remote assessments, is an important growth area for wearable technology.

Monitoring and Intervention

Although researchers have extensively explored the use of wearable technology for outpatient monitoring, only a few medical-grade systems exist. Potential target patients range from those with heart arrhythmia and others at risk of heart failure to fragile walkers with a high risk of falling. Wearable monitoring systems are also an ideal tool for tracking many health-relevant behaviors, activities, and consumption habits as well as physiological responses (such as arousal, stress, and emotions) and cognitive performance. The next crucial development step for wearable technology is intervention—for example, in glucose level management and behavior guidance. More progress in context recognition research is necessary to yield robust wearable intervention systems.

Integrating Wearable and Clinical Big Data

Integrating data from clinical sources and wearable monitors provides the potential to yield new biomedical knowledge. In particular, clinical and wearable data complement each other in coverage (the lab versus anywhere), fidelity (exact diagnostics versus estimates and noisy measurements), and supervision (supervised versus unsupervised/free living). As wearable use increases and more clinical data becomes accessible through new data interoperability standards, researchers will gain new knowledge by combining these two data sources. There will be greater insight into treatments' effects in free living and better diagnostic evidence. Physicians and therapists will be able to adjust both clinical treatments and wearables' monitoring and intervention functions continuously for each patient.

Health Education

Outside the healthcare and research communities, the many existing and potential benefits of wearable health technology are not widely known. Wearable health education initiatives along with virtual coaches are needed to promote and sustain use of this technology among the public, beyond wearable enthusiasts, lifeloggers, and a limited number of well-informed patients.

INTEGRATING BEHAVIORAL, GENOMIC, AND ENVIRONMENTAL EXPOSURE DATA

Perhaps the most profound potential of digital health lies in integrating health-related behavioral data with personal genetic information and environmental-exposure data to identify individual health risks and ideally prevent diseases before they occur.[15] While health risks might originate from a genetic predisposition, environment and behavior are modulating health risks and can introduce additional ones. The health implications of living in an air-polluted area or smoking are two well-known examples.

Christopher Paul Wild denotes the monitoring, measuring, and modeling of a person's lifetime environmental exposure, or exposome, as exposomics,[16] analogous to the sequencing and mapping of the human genome, or genomics. Since 2013, various large EU and US research projects have investigated the exposome from prenatal to adult life, including air, water, and food pollutants. These projects have integrated on-body measurements from available technology, mostly smartphones and a few additional sensors. Rapid sensor and wearable development will likely expand the ability to cover most environmental variables, maximize regional coverage, and provide long-term statistics.

The exposome includes well-known lifestyle factors important to health such as alcohol use, diet, and exercise. However, health is also impacted by other aspects of human behavior such as social contact, daily activities, and mental attitude. Inspired by Darryl Macer and Masakazu Inaba's term behaviorome, which refers to the spectrum of human ideas,[17,18] I refer to all health-related behavior as health-behaviorome.

As Figure 3 shows, wearable computing technology is critical to the digital health vision because it offers the ability to continuously assess an individual's exposome and health-behaviorome. Integrating exposome and health-behaviorome data with genetic data will make it possible to implement personalized risk prevention and treatment strategies.

WEARABLES IN FUTURE MEDICINE

Wearable computing is beginning to assume a prominent role in digital health, but distributed information sharing and health data integration is still largely a vision. To leverage wearables' full potential, researchers must address several technical challenges (some of these were discussed in the previous "Wearable Computing" department[6]). The most critical relate to validity/reliability and long-term compliance.

Navigating the current health devices market is tedious even for the technically savvy and is at least murky for most users and healthcare professionals. Research has debunked the oft-claimed one-device-can-do-it-all paradigm, which presents a challenge for physicians of which devices to prescribe. The solution likely involves

- scalable validation methods and proper medical study results,
- navigation tools to identify adequate (ideally validated) wearables, and
- novel procedures to address the tradeoff between market size and development effort.

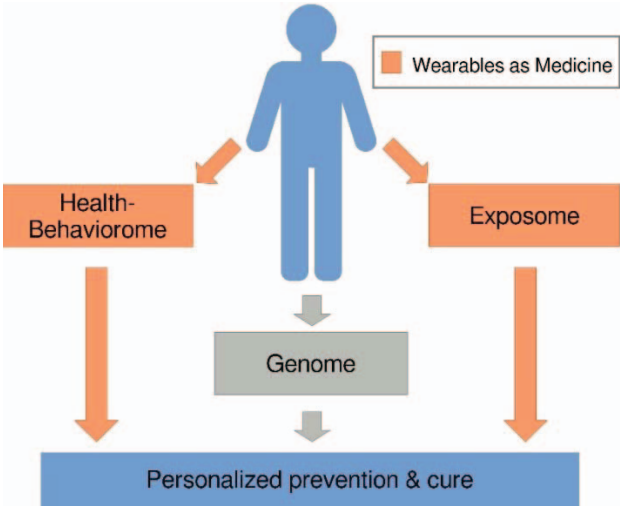

Figure 3. Integrating an individual's exposome and health-behaviorome, obtained through wearables, with genetic data will make it possible to implement personalized risk prevention and treatment strategies.

Digital health benefits from wearables will only be realized through routine use potentially over many years. Yet, many current wearables have demonstrated critical compliance problems. Progress on several frontiers might address this challenge too:

- health information must be continuously delivered to users like the weather and news through automated education services;
- actively dealing with and communicating uncertainty in estimated information may help build users' trust in wearable health devices; and
- innovative device design must align with wearers' needs and preferences, not vice versa.

CONCLUSION

Wearable computing is shaping digital health in several ways. First, wearable computing is fostering a transition in the way health data is created, stored, processed, and managed from the traditional model of centralized IT systems to a new model of distributed information sharing with patients and users rather than providers, insurers, and other industry stakeholders at the center. Second, the integration of vital-sign and other wearable data with clinical data is leading to new health knowledge and techniques. Third, wearables are ideally suited to capture health-related behavioral and environmental exposure data, which can complement genetic data to more effectively prevent and treat chronic diseases and thereby gain quality life-years. Progress must be made on several fronts to address wearable computing's current technical challenges, but the promise of profoundly improved health outcomes and more personalized prevention and care makes such endeavors worthwhile.

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