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Digital Biomarkers: Engineering Tools for Personalized Health Tracking

Omukisa Kireba K.

Faculty of Science and Technology Kampala International University Uganda

ABSTRACT

Digitization of healthcare is revolutionizing the generation, analysis, and use of health information, with digital biomarkers in the vanguard. Digital biomarkers—quantitative and objective physiological and behavioral data collected with digital sensors—offer a novel category of health indicators that can allow for constant real-time observation and personalized management of health. This paper describes the multifaceted ecosystem supporting digital biomarker development, such as advances in sensor technologies, data gathering and analysis methods, mobile health apps, and artificial intelligence. It categorizes the different types of digital biomarkers, evaluates their application in clinical and consumer health settings, and addresses personalization challenges, ethical use, and data protection. Additionally, it identifies applications and trends like the application of blockchain for secure data management and engineering to develop scalable biomarker models. The review brings into perspective interdisciplinary collaboration as crucial in maximizing the potential of digital biomarkers for improving precision health without compromising responsible innovation and equality of access.

Keywords: Digital Biomarkers, Wearable Technology, Personalized Health, Mobile Health (mHealth), Real-Time Monitoring, Sensor Data.

INTRODUCTION

The sequential and intensifying digitization of our modern society is deeply transforming the way healthcare provision takes place through a well-controlled blend of technology, policy, and economics. The growing accessibility of low-cost and highly sophisticated sensor technology through the emergence of convenient and ubiquitous devices has tremendously and fundamentally reduced the costs incurred in data generation and collection exercises. This new trend, along with continually falling computing power and falling data storage costs, is evolving into a healthy and highly productive data mining and management business that is quickly gaining momentum. Furthermore, the large-scale shift away from traditional patient-managed care towards more structured managed care is driving an expanding demand for non-invasive computerized devices specifically designed to monitor health continuously and in real-time. Many frequently costly and complex healthcare complications, particularly those related to chronic disease, are the consequence of insidious changes in health that typical episodic clinical encounters frequently fail to detect and even entirely miss. As increasingly prevalent creation of health data becomes rooted in healthcare systems, "digital biomarkers" will become significant and critical indicators of health and disease status, complementing traditional biomarkers with far more detailed and richer data. These new digital biomarkers can potentially alter the complex dynamics of the doctor-patient relationship, as well as the entire healthcare delivery model, by introducing new and diverse stakeholders to the equation. Understanding of the unprecedented potential and intrinsic challenges posed by these novel digital "monitoring" biomarkers is essential in addressing properly anticipated issues, as well as enabling the promotion of the regulated and responsible utilization of these groundbreaking technologies in wellness solutions. The overall focus is on building "domain-specific" biomarkers that efficiently map diverse signals into meaningful and useful information about health, thereby supplementing traditional biomarkers with effectively and systematically transforming high-level sensor measurements to comprehensible health indices easily interpretable and actionable [1, 2].

The Role of Technology in Health Tracking

Concurrent with increased public interest in health awareness, technologies and methods for understanding states of health are evolving. Wearable biosensors are prevalent, enabling live monitoring of physiological data. Mobile computing and telecommunication advancements provide inexpensive, large-scale mechanisms for continuous health tracking through telehealth systems. Quantified digital information-based digital biomarkers provide an objective measure of health, in contrast to traditional Knowledge-based Personal Health Trackers (K-PHTs), which rely on user-provided subjective feedback on health and behaviors. As opposed to single-point laboratory measurements, digital biomarkers offer dynamic, rich flows of information. Digital health technologies vary based on the technical basis, data form, and use. They extend from low-level devices like pedometers to sophisticated systems that can combine data from more than a single bio signal. Current biosensors yield rich data, allowing multidimensional information to be derived. Advanced multi-modal tracking systems utilize an amalgamation of sensors in tandem, combining health markers into a composite tracking tag. The systems coordinate readings of disparate signals and provide both clean physiological data as well as composite digital biomarkers. AI being incorporated into these systems fortifies them to detect outliers and manage parameters before sending the data to cloud platforms through smartphones [3].

Types of Digital Biomarkers

Digital biomarkers are known as information recorded and measured by a mobile phone that can be used to find, validate, or monitor clinical outcomes and evaluate pharmaceutical products throughout development. They are quickly becoming a fertile ground for development focused on the inferential and clinical worth of human-generated digital information 4. While computers, laptops, tablets, smartphones, and Wi-Fi continue to spread, so does the volume of passive data generated about individuals' social behavior, mood, cognition, and language use. The quick emergence of wearables has stimulated a blast in the demand for monitoring physical movements, physiological activity, exposure to the environment, and even social behavior and language use as digital disease and health biomarkers. There are various digital biomarkers. Initially, an open digital biomarker can be described as one form of digital biomarker that has been made and distributed to the public so that other scientists can re-test, reproduce, and/or re-use them through the open internet. Secondly, there are reformulated and/or validated open digital biomarker(s). They are different from the first form of open digital biomarker in the sense that they have been modified for a novel application or usage. They have been reconfigured to produce an alternative form of the signal that could be useful in other applications or confirmed in a new population. Digital image, audio, and sensor recordings are examples. Digital biomarker should not be of a "well-understood/identified" behavioral pattern or a "computer model that relates the image to the environmental factor retrieved." Indicate which of the below-listed explicit parameters of the outcomes are to be used as a digital biomarker in independent investigations, and what this means in terms of advantages and/or limitations of the digital biomarker. Describe a specific computational technique for extracting a type of digital biomarker(s) from raw image, audio, and/or recording. Attempt to describe limitations and challenges in terms of addressing these issues using the specific type of data and possibilities in the future. Provide reasonable speculation given the virality of the readily available digital data and existing computational constraints [5, 6].

Data Collection Methods

Data are increasingly available in the form of streams of human health, behavior, and their social context from mobile smartphones, wearables, social media, electronic health records, public health systems, health service systems, and genomics. These sources can potentially produce real-time streams of continuous human-generated health and behavior information. The most well-known uses of such streams are in tracking health and ease of patient behavior. These data streams have great applications across various fields. All data sources can be captured in real-time and over time continuously, revealing the possibility of entirely new kinds of analysis. As health data becomes increasingly available, blockchain technologies can be leveraged to keep data securely and privately stored in the 21st century and enable fine-grained sharing and access control. Employ novel techniques for bias prevention to enable health scientists to build data sets from many different sources in manners that maintain minimal diversity bias within the data set. Develop rigorous procedures for matching between unlike data sets with implications extending towards study enrollment, longitudinally tracking patients' status between and across studies, and composite real-time warning systems. Design prediction algorithms to exploit data from possibly more than a dozen or so different sensors/applications to detect numerous different human activities/behaviors of interest. Health measurement tools can be scaled along a continuum from clinical to more consumer-oriented, and most clinical instruments will be more expensive and require special training to deliver and interpret. Historically, these have been pencils and paper. During the last decade, new technologies for the delivery of these tools to consumers and the collection of their data have been evolving at a fast pace, with enhanced capabilities for supporting new types of data and converting data flow from episodic and intermittent to continuous and real-time [7, 8].

Data Analysis Techniques

Progress in unobtrusive, wearable sensors that measure human physiology has made for an ideal platform for health monitoring and the detection of clinical events. Sleep and inactivity spell behaviour can now be measured unobtrusively during the day. Blood pressure, heart rate, respiration, and skin conductance have also been investigated, and individual variation characterized. There are also attempts at measuring basal body temperature, blood glucose, and other parameters that require more invasive instrumentation. One new field of mobile health (mHealth) is focused on making such measurements unobtrusively but continuously in the hope of engineering digital biomarkers. The mHealth class of general application collects and analyzes corresponding health data with wearable sensors or cellular phones. mHealth is expected to be a $23 billion market in the year 2017 and is most likely to keep on expanding. Computer science and engineering are newcomers to the life sciences. Before, biology and data analysis were separate fields. The rapidly expanding biological data on all scales has forced biologists to come up with more computational sophistication. Application of these data in predictive modeling, hypothesis testing, and experimental design necessitates mathematics, statistics, and computer science knowledge. Again, however, these areas were split traditionally, and thus, rooms, buildings, departments, and universities were set aside for these different areas. No single person possessed expertise in all four of the areas needed to solve problems from such multi-dimensional data. The ideal solution is collaboration between trained biologists and trained engineers in biomarker engineering. There are places where biologists and engineers can collaborate in many venues. Academic activity varies from formal programs to research collaborations. More and more engineers enter biomedical or health-care programs with a strong interest in biological ecosystems. Others pursue more formal postdoctoral training with a focus on training engineers in biology. There are equally promising prospects for educated biologists to enter industry or begin careers in engineering. Translational bioinformatics will enable engineering-scale datasets to be accessed to discover biomarkers, hypotheses, and therapeutics [9, 10].

Personalization In Health Tracking

The explosive growth of wearable technology and mobile health applications provides a tremendous chance to enhance public health. These technologies can capture high-fidelity data about user behavior and create digital biomarkers. Each individual has a unique physiological status, either healthy or symptomatic, which makes the "one-size-fits-all" biomarker strategy challenging. The shift is towards personalization in digital biomarkers, either through different computations on identical sensor data or by adapting data collection strategies. Both forms of personalization are required for developing robust and clinically valuable digital biomarkers. Current aggregated measures used in wearables and health apps fail to capture the wealth of information in the data. Advanced statistical models are needed to properly estimate complex digital biomarkers for activity and food intake behavior. These models, though, come with increased computational load and potential for inaccuracy due to mis-specification. The goal in personalized engineering is to create function classes that adapt to both individual profiles and sensor data, enhancing performance through tailored parameters. Challenges arise in personalizing long-term health monitoring with varying device hardware and data collection settings, where achieving a unified function across diverse individuals becomes increasingly difficult. The technical diversity aimed at improving usability further complicates health tracking efforts [11, 12].

Ethical Considerations

The increasing use of digital sensors in health presents numerous ethical concerns over the impact of such technology on what constitutes normal, the fate of health professionals, and people's autonomy. Although the ethical implications of the use of digital sensors in medicine are already known, the investigation of ethical design needs to avoid unwanted side effects is still critical. The subsequent ethics of design guidelines for makers of digital disease biomarker devices are established accordingly: Form-follows-function with the subject as an empowered user, Model-of-normal-variation usage, Open health danger management and systems performance dashboards, Instruction procedures providing situational instruction before use, Care for self-enhancing feedback loops and addictive forms of design patterns, and Assurances of life-long autonomy through openness of the estimated models. Digital diseases can be defined as medical illnesses caused by digital devices performing tasks historically equivalent to human senses and intelligence, such as environmental monitoring, knowledge management, for for-profit, and with potential adverse health side effects. Among the core issues for personalized health management is the selection of health-related variables (biomarkers). There are two quite distinct classes of digital disease biomarkers (DDBMs): A digital sensor-based and an engineering or IT-related form of definition. Unlike medical conditions implied from a population model of normality, DDBMs' impact reflects the social and subjective character of health literacy. In addition, like any other product designed, the design of an introductory event has long-term effects on the user behavior validated within. There are ethical and practical issues that do not exist with controlled medical devices [13, 14].

Challenges To the Implementation of Digital Biomarkers

Expertise & Training. Ease of use is also needed when economic, engineering, computer science, and software development expertise exist. Users are often impaired in complex statistical realms without benchmarking. Adopting a Chatham House rule will enhance risk investment in mHealth initiatives, as companies will not invest without protecting intellectual property rights. Probabilistic framing will encourage mass use by providing predictive ranges, especially in novel behavior analysis potential. Fortunately, most first-world citizens own smartphones with enabling technology, so user downloads can facilitate testing. Users need to contribute to public-facing and model training studies to protect UI integrity. Development toolkits are available, with new business models for broad adoption. Computational modules can be separated from the UI to address transmission issues, with several devices being able to connect securely. Of special note, there's a feature of simultaneous video streaming from smartphones and smart glasses. Data from various dashboards can be merged, and user-friendly interfaces are made available by third-party developers. For instance, a smart impact ball game involves participation with the facilitation of sharing information. Any healthcare software is adjustable to enable text reminders at ease and facilitates mHealth interventions in crowded environments or monitoring players' behavior in real-time. Simple solutions are dependent on the prediction of information intensity from sensor streams to overcome market complexity and regulation issues [15, 16].

Case Studies of Digital Biomarkers in Use

Smartphones are a feasible and inexpensive platform for health measurement devices. The heterogeneous embedded sensors in devices have progressively increasing sampling rates and resolutions, and there is a growing body of evidence that demonstrates they can be used to measure new health metrics pertinent to disease monitoring. However, the majority of the proposed metrics that exist today are described as both intent-designed and computed by the resulting algorithm implementation. The complementary and comparative application of engineered and raw measures represents two competing paradigms of measurement. There is significant interest in compounding aggregated measures, typically generated by cluster algorithms, to represent a more high-dimensional construct of health. The rate of digital health technology development has allowed for the development of previously unthinkable, high-resolution digital measures of health and behavior. These Digital Monitoring Biomarkers (DMBs), i.e., an encoded, calibrated reading taken from an engineered process or device of measurement to capture a biologically meaningful construct of a person's behavior or health status, could potentially change the game when it comes to monitoring health and behavior. DMBs represent one attempt at grand innovations in precision health with a possible likelihood of horrendously disastrous risks. Mitigating the technical, ethical, social, and economic implications of DMBs will be key to averting more health inequities and to precluding co-created negative behaviors. Advances in the engineering of DMBs must be accompanied by full consideration of the wider implications of their use [17, 18, 19].

Future Trends in Digital Biomarkers

As popular mental computer science like wearables, scroll computing, and big data evolved, digital biomarkers were created. New measurement techniques for digital biomarkers and new opportunities were created. New digital biomarkers engineering approaches, such as non-invasive, accurate neuroimaging with a small number of mobile sensors, low-cost device-based multi-parameter and multi-scale digital biomarkers, and clock-synchronization-free localization protocols with cellular towers, have been proposed recently. New challenges and opportunities emerge every day with the growing research interest in digital biomarkers from industry and academia. This paper provides an overview of the digital biomarkers engineering approach, including at first the four components of a digital biomarker: data acquisition, signal processing and brain modeling, data analysis, and using. The most recent developments and advancements of these components will be introduced. The future directions will be discussed, including establishing an operational digital biomarker library, a global data-sharing platform for digital biomarkers, and identifying a potential new biomarker of this type. Wearable biosensors, smartphones, and other devices monitor body conditions and screen a wide range of health conditions, resulting in digital versions of physiological and behavioral or activity biomarkers. With careful consideration, preprocessing of data, and subsequent thoughtful analysis, digital data from wearables or smartphones can provide digital health information. The biomarkers generated by digital data streams for monitoring health conditions are called digital biomarkers, which can be classified into digital monitoring and authentication biomarkers. Cardinal digital monitoring biomarkers (dMBs) are a new, valuable use of digital health [20-23].

CONCLUSION

Digital biomarkers are a paradigm shift in healthcare by enabling continuous, personalized monitoring outside the clinical setting. They are fueled by innovations in wearable technology, mobile computing, and cloud-based analytics, which enable the capture of complex and dynamic health data. As digital biomarkers evolve, not only do they augment traditional clinical markers, but they also allow individuals to engage more actively in their health experiences. But digital biomarker adoption into mainstream medicine also comes with a unique set of challenges, ranging from computational and interoperability concerns to ethical and privacy concerns. Addressing these concerns will require a multidisciplinary approach, involving engineers, clinicians, data scientists, ethicists, and end-users. Through the establishment of robust data governance models, privacy frameworks, and equitable access strategies, digital biomarkers have the potential to significantly boost the accuracy, efficiency, and inclusiveness of healthcare systems worldwide. The future lies in harnessing this technology to fill care gaps, forecast and prevent disease progression, and personalize interventions with unprecedented precision.

REFERENCES

1. Vasudevan S, Saha A, Tarver ME, Patel B. Digital biomarkers: convergence of digital health technologies and biomarkers. NPJ digital medicine. 2022 Mar 25;5(1):36.
2. Alonso AK, Hirt J, Woelfle T, Janiaud P, Hemkens LG. Definitions of digital biomarkers: a systematic mapping of the biomedical literature. BMJ Health & Care Informatics. 2024 Apr 8;31(1):e100914. nih.gov
3. Liu J, Dong S, Gai S, Li S, Dong Y, Yu C, He F, Yang P. Four Birds with One Stone: A Bandgap-Regulated Multifunctional Schottky Heterojunction for Robust Synergistic Antitumor Therapy upon Endo-/Exogenous Stimuli. ACS nano. 2024 Aug 16;18(34):23579-98. [HTML].
4. Kovalchick C, Sirkar R, Regele OB, Kourtis LC, Schiller M, Wolpert H, Alden RG, Jones GB, Wright JM. Can composite digital monitoring biomarkers come of age? A framework for utilization. Journal of clinical and translational science. 2017 Dec;1(6):373-80.
5. Motahari-Nezhad H, Al-Abdulkarim H, Fgaier M, Abid MM, Péntek M, Gulácsi L, Zrubka Z. Digital biomarker–based interventions: systematic review of systematic reviews. Journal of Medical Internet Research. 2022 Dec 21;24(12):e41042. jmir.org
6. van den Brink W, Bloem R, Ananth A, Kanagasabapathi T, Amelink A, Bouwman J, Gelinck G, van Veen S, Boorsma A, Wopereis S. Digital resilience biomarkers for personalized health maintenance and disease prevention. Frontiers in Digital Health. 2021 Jan 22;2:614670. frontiersin.org
7. Steenwinckel B, De Paepe D, Vanden Hautte S, Heyvaert P, Bentefrit M, Moens P, Dimou A, Van Den Bossche B, De Turck F, Van Hoecke S, Ongenae F. FLAGS: A methodology for

adaptive anomaly detection and root cause analysis on sensor data streams by fusing expert knowledge with machine learning. Future Generation Computer Systems. 2021 Mar 1;116:30-48. sciencedirect.com
8. Chen J, Chen S, Fu R, Li D, Jiang H, Wang C, Peng Y, Jia K, Hicks BJ. Remote sensing big data for water environment monitoring: Current status, challenges, and future prospects. Earth's Future. 2022 Feb;10(2):e2021EF002289. wiley.com
9. Choe EK, Klasnja P, Pratt W. mHealth and Applications. InBiomedical Informatics: Computer Applications in Health Care and Biomedicine 2021 Jun 1 (pp. 637-666). Cham: Springer International Publishing. [HTML]
10. Steinhubl SR. Where mobile health technologies are needed in healthcare. InmHealth Innovation 2021 Mar 24 (pp. 287-295). HIMSS Publishing.
11. Doan TN. An efficient patient activity recognition using LSTM network and high-fidelity body pose tracking. International Journal of Advanced Computer Science and Applications. 2022;13(8). [HTML]
12. Islam M, Rashid S, Rafid L, Badrul T, Islam A, Chaudhry BM. Design and Evaluation of a Smartwatch-Based Physiological Signal-Driven Workplace Stress Management mHealth Tool for Bangladeshi Healthcare Professionals. In2024 Advances in Science and Engineering Technology International Conferences (ASET) 2024 Jun 3 (pp. 1-10). IEEE. [HTML].
13. Ongesa TN, Ugwu OP, Ugwu CN, Alum EU, Eze VH, Basajja M, Ugwu JN, Ogenyi FC, Okon MB, Ejemot-Nwadiaro RI. Optimizing emergency response systems in urban health crises: A project management approach to public health preparedness and response. Medicine. 2025 Jan 17;104(3):e41279.
14. Goldsack JC, Dowling AV, Samuelson D, Patrick-Lake B, Clay I. Evaluation, acceptance, and qualification of digital measures: from proof of concept to endpoint. Digital biomarkers. 2021 Mar 23;5(1):53-64. karger.com
15. Ugwu CN, Ugwu OP, Alum EU, Eze VH, Basajja M, Ugwu JN, Ogenyi FC, Ejemot-Nwadiaro RI, Okon MB, Egba SI, Uti DE. Sustainable development goals (SDGs) and resilient healthcare systems: Addressing medicine and public health challenges in conflict zones. Medicine. 2025 Feb 14;104(7):e41535.
16. Marsch LA. Digital health data-driven approaches to understand human behavior. Neuropsychopharmacology. 2021 Jan;46(1):191-6.
17. Hu Z, Wang Y, He M, editors. Advances in intelligent systems, computer science and digital economics III. Springer International Publishing; 2022 Mar 10.
18. Purnomo A, Susanti T, Rosyidah E, Firdausi N, Idhom M. Digital economy research: Thirty-five years insights of retrospective review. Procedia Computer Science. 2022 Jan 1;197:68-75. sciencedirect.com
19. Nneoma UC, Fabian O, Valentine EH, Paul-Chima UO. Innovations in Renewable Energy for Health Applications. system. 2025;1:2.
20. Kyriazakos S, Pnevmatikakis A, Cesario A, Kostopoulou K, Boldrini L, Valentini V, Scambia G. Discovering composite lifestyle biomarkers with artificial intelligence from clinical studies to enable smart ehealth and digital therapeutic services. Frontiers in Digital Health. 2021 Sep 6;3:648190. frontiersin.org
21. Blendea L, Miler AA, Csabai J, Trifan A, Gurzu IL, Novac B, Novac O, Petroaie AD, Balmus IM, Timofte DV. From Traditional Medical Patterns to Artificial Intelligence: The Applicability of Digital Biomarkers in Reinventing Personalised Nutrition. BRAIN. Broad Research in Artificial Intelligence and Neuroscience. 2025 Apr 6;16(1 Sup1):179-92. edusoft.ro
22. Bent B, Cho PJ, Henriquez M, Wittmann A, Thacker C, Feinglos M, Crowley MJ, Dunn JP. Engineering digital biomarkers of interstitial glucose from noninvasive smartwatches. NPJ Digital Medicine. 2021 Jun 2;4(1):89. nature.com
23. Asare KO, Moshe I, Terhorst Y, Vega J, Hosio S, Baumeister H, Pulkki-Råback L, Ferreira D. Mood ratings and digital biomarkers from smartphone and wearable data differentiates and predicts depression status: A longitudinal data analysis. Pervasive and Mobile Computing. 2022 Jul 1;83:101621. sciencedirect.com

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