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Human digital twin initiatives

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Abstract

This study provides a review of the Human Digital Twin (HDT) initiatives from the United States, the European Union, and international organizations such as World Health Organization and North Atlantic Treaty Organization. The aim is to characterize the context, progress, scope, and scale of their initiatives and programs. The study utilized a literature search to identify global and national-level efforts germane to human performance optimization and precision medicine. The results of the study show that the HDT teams are in the forming stage of development. Teams focus on injury and disease HDT applications. HDT programs, projects, and prototypes emphasize usages by human performance professionals and medical teams rather than by the twinned human. Technical development continues in networking sensors, multi-modality data rendering, and mechanistic and statistical model integration across disciplines and scales. While consensus on future technical directions emerge with national and international collaboration, gaps in foundational knowledge of human biology and how to best digitize and develop such knowledge remain. These findings are useful for information system architects and designers to derive requirements for developing fit for purpose HDTs.

Keywords: digital twin, human digital twin, artificial intelligence, human digital model, human simulation

Introduction

Giddens (1990) stated that modernity is a double-edged phenomenon. For example, the consequences of modernity added years to life and life to years with sanitation, electrification, and transportation while taking years from life and life from years with air and water pollution, soil contamination and nutrient depletion, and social isolation and loneliness via social media. In the last half century, modernity delivered computerization, digitalization, and virtualization of many lives and things, natural and engineered. The investments to develop computer models, digital replicas, and virtual twins as tools and products keep on going. The human digital twin (HDT) is one of such efforts in the initial phase of development. A HDT in in healthcare currently implies dynamically modeling of a whole human, an organ system, lesser anatomical structures such as tissues, cells, and genomes to estimate outcomes from possible medical interventions.

Digital twins have been applied in diverse fields such as manufacturing and environmental management. Kuehnera et. al. (2021) conducted a meta-study on digital twins, which showed various applications of digital twins. There is academic literature on HDT research and development as well. Lauer-Schmaltz et. al. (2024) surveyed human digital twins. Katsoulakis et. al. (2024) also conducted a scoping review on digital twin for health. Tang et. al. (2024) provided a roadmap for human digital twin research.

Different from studying the literature in academic research, this research focuses on HDT initiatives of national and international organizations. This research examines the status of HDT initiatives by the governing organizations. Specifically, this study seeks to examine and compare the initiatives (or lack of)

in HDT by the United States, European Union, and international organizations such as World Health Organization, North Atlantic Treaty Organization, etc.

Background

Digital Model, Digital Shadow and Digital Twin

Xames and Topcu (2024) articulated the important distinctions of digital twins and twinning that many researchers do not understand or disregard when labeling and positioning their work in the literature. A major distinction is in the connectivity between the physical object and its digital object. Figure 1 illustrates the connectivity differences among a digital model, digital shadow, and digital twin (Xames and Topcu, 2024). Similarly, Mulder et al. (2022) emphasized that digital twins are executable in a computing environment with bidirectional communications with their physical counterparts.

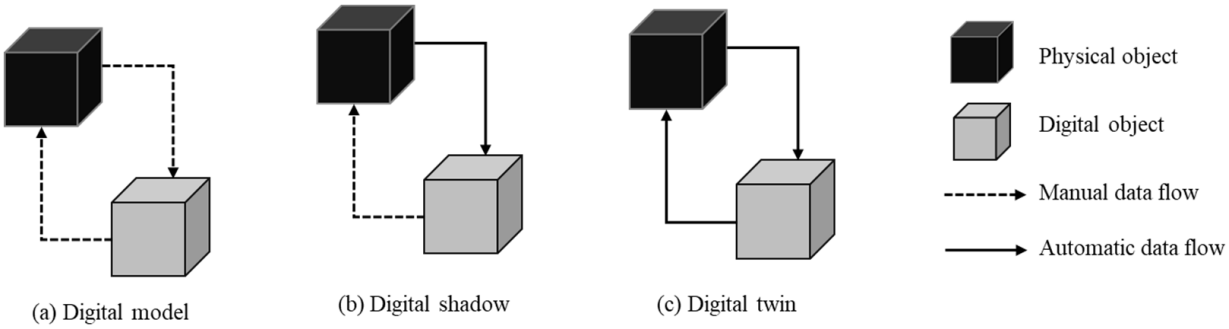

Figure 1: A visualization of (a) Digital model, (b) Digital shadow, and (c) Digital twin. (Xames & Topcu, 2024)

In 2002, the term digital twin was coined as a product life cycle management innovation after years of using digital shadows (DS) (Greives, 2023). As DT was evolved from DS, DS was evolved from digital models (DM). A DM is a mathematical abstraction of phenomena implemented in software using first principles (i.e., physics) and a data-driven abstraction of a physical asset, natural and/or manufactured. The DM of a physical asset usually is accredited for a specific purpose after its built, verification, and validation, which quantifies its uncertainties of structural configuration and behaviors in controlled operating environments. But real-time communication between a physical asset and its DM does not occur. A DS, on the other hand, is a DM processing real-time data from its physical asset's sensors so that the DS evolves with the physical asset. A DT is a DS with two-way, real-time communications between the physical asset and the DS. The DT changes are based on the telemetry from the physical asset. The physical asset may change based on actionable possibilities computed with its DT in forecasted environments.

The National Academies of Sciences, Engineering, and Medicine (NASEM) defines "a digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value" (NASEM, 2023). NASEM (2023) emphasizes that the bidirectional interaction between the virtual and the physical is central to the digital twin, and a digital twin is more than just digital modeling or shadowing.

Due to the bidirectional and real-time interaction between a physical asset and its digital twin, the data acquired from the physical asset and stored in the digital twin for analysis is often times big data, especially

for complex decision making. The predictive capability and decision support analytics from the digital twin that realize timely value to the physical asset involves artificial intelligence (AI) as AI has the capability of analyzing big data and providing prediction in a timely manner.

Human Digital Twin – Complexity and Challenges

A human digital twin (HDT) is a specialization of digital twin (DT) because it applies to the human while DT can apply to inanimate physical entities. When there are no real-time communications between a human and its digital model, the executable digital model is just a human digital model. When the real-time communication is solely one-way, from a human to its digital model, that is human digital shadowing because the model is synchronized with its human data source.

The concept of a human digital twin and human digital twinning is a lofty vision because it has the potential to mitigate some root causes of poor health, lacking of fitness, and falling short in performance. Figure 2 below illustrates a hierarchy of spatial scales for multi-dimensional data collection, computation, and management that sensors could stream or sample human anatomy and behaviors at both micro and macro levels. The human is composed of trillions of cells that are differentiated into over 200 types of cells. These types of cells are the building blocks for four (4) basic kinds of tissues, 80+ organs, and 12 organ systems. Adding to the complexity of cells and organ systems is their interaction with huge varieties of bacteria, fungi, and viruses in the quantity much larger than that of human cells. The genomic level of human is a fledging field of science where AI has played a critical role in facilitating filling the gap of understanding of human biology at its foundational details. The big data regarding human well-being including societal aspects and whole human including context also require big data technology and AI for modeling, analysis and prediction. Building cognitive, mechanistic, physiological and human-in-the-loop HDT, as illustrated in Figure 2 is challenging simply due to the complexity of human and human context. Not to mention the difficulty of digitizing such a complexity and bi-directional real-time interactions between human and HDT.

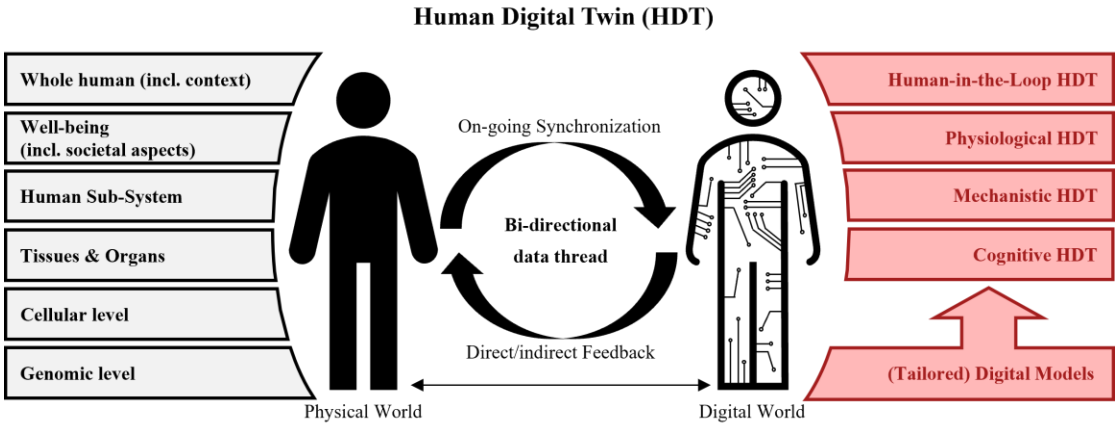

Figure 2: A General Conceptualization of Human Digital Twin (Lauer-Schmaltz et al., 2024)

HDT faces technical and computational challenges. Even when abstracting out the electrons, electromagnetic fields, atoms, and molecules that comprise organelles to model human biological processes, pathophysiological trajectories effected by pharmaceuticals, from the gut outwards or skin inwards, it is still difficult for one to realize how computationally intractable this becomes beyond a few seconds for the whole body. The memory and processing capacities to integrate microscopic particles with nanosecond time steps over human-scale volumes for only a few minutes is a non-starter.

The HDT literature does not have computational thresholds in theory for the use cases and applications under development yet, only the descriptions of intended use cases and applications. The HDT literature does not have strata of the grade or quality of human digital simulations, near real-time or asynchronous. The HDT literature does not specify what classes of computers (e.g., smartphone, engineering workstation) are capable of now, in 2030, and beyond. The coverings the human is wearing and with the ambient environment the human is performing tasks are tantamount specifications for simulating the HDT and merely archiving in synchrony with biotelemetry. Hence, researchers face unsolved problems of coupling multi-physics models across timescales without exceeding uncertainty constraints to be actionable by the human and/or its performance and care team.

Methodology

This study employed a literature search of HDT visions, revolutions, frameworks, architectures, models, blueprints, plans, implementations, technologies, surveys, and reviews with selected papers on digital health. The HDT literature is scattered over the landscape of academic, government, and industry publications without a seamless, standardized structure to track the fulfillment of capability gaps at all scales and dimensions of a human's 110+ year life course (prewomb to tomb) including its external contexts (i.e., indoors and outdoors). Researchers and readers do not have an encyclopedic reference or a HDT ontology to communicate and collaborate on an evolving definition of comprehensive human being with digital models, simulators, and networked sensors and effectors for digital twinning. Nonetheless, in order to understand the intentions of the U.S., EU, and international organizations (i.e., World Health Organization, North Atlantic Treaty Organization, International Standardization Organization, and Institute of Electrical and Electronic Engineers), this study focused on HDT publications from these governmental agencies (i.e., National Science Foundation, National Institutes of Health, Advanced Research Projects Agency for Health, National Aeronautical and Space Administration, Department of Defense, Department of Health and Human Services, European Commission) to understand their intentions, stakeholders, and results at the strategic level. This study examined the HDT literature that was organized, funded, or sponsored by the U.S., the EU, and international organizations.

Results

Human Digital Twin – International Initiatives

Since the word "human" is unrivaled at modifying digital twin when referring to any specific part, condition, or role of a human, the obvious coordinator for the unqualified HDT should be the World Health Organization (WHO) from a medical context and the Olympic committee from a performance context (i.e., Junior, Para, Senior, and Military World Games). For tactical athletes, the North Atlantic Treaty Organization (NATO) Science and Technology Organization (STO) interest in HDT is studied.

The term, HDT, is neither in the WHO's 2024 global initiative on "Digital Health: Coordinated support for country-led digital health transformation" brochure nor in its global strategy on digital health 2020-2025. The WHO language in its initiative and strategy should not preclude HDTs because HDTs are considered one of the digital solutions, which should be a part of the WHO's efforts.

In November 2023, the NATO STO Human Factors and Medicine (HFM) panel and NATO Modeling and Simulation Group (MSG) started an exploration of the use of the HDT in the military. The activity will neither prototype a HDT nor collect data useful in developing a HDT. Using themed panels, the Research

Specialists' Meeting (RSM) will understand military relevant HDT applications. In December 2024, the RSM will host a four-day oral presentation on human digital twins in the military on its findings and perspective. The topic areas include military HDTs' challenges and opportunities, HDTs impacts on military operations, HDTs in military equipment design, military HDTs' legal, ethical, and social implications, HDT data security, HDTs usability and scalability, HDT visualization, and HDT integration with support systems. By November 2026, the research specialists will publish a report inclusive of common terms, use cases, and its vision for HDT applications in the NATO.

In academia, there is a global collaboration on HDT development. For example, in October 2023, the Frederick National Laboratory for Cancer Research, Brookhaven National Laboratory, in the United States and the University College London organized a two-day Virtual Human Global Summit (VHGS) at the State University of New York for thought leaders from across the globe (VHGS Committee, 2024). The program had five themes: virtual human models and biomedical digital twins in research; infrastructure and environments for digital twins in biomedicine; biomedical digital twins in practice; supporting biomedical digital twins; and community adoption and path forward for medical digital twins.

Human Digital Twin – United States' Initiatives

The National Aeronautics and Space Administration (NASA) has been modeling human performance in aerospace environments since the Space Race started in the 1950s. With renewed plans to build lunar outposts in the 2030s, the NASA Office of the Chief Health and Medical Officer has sponsored a small business innovative research project for a Human Digital Twin Platform (HDTP) (NASA, 2023). The project will deliver a virtual counterpart of a person's biological and physiological presence in the Metaverse. The HDTP will enable the creation of a custom, real-time 3D, photo-realistic avatar and combine it with an always-on, real-time physiological monitoring system that uses commercial off-the-shelf wearables.

The U.S. Congress established the Advanced Research and Projects Agency for Health (ARPA-H) in 2022 to manage 1.5 billion tax payers' dollars in appropriations annually for high-risk, high-reward research and technology programs in four areas, one being Proactive Health (ARPA-H, 2024). The tagline for the Proactive Health focus area is "keeping people from being patients", which is the desired outcome for any program deliverables integrated into Americans' lifestyles. Of the fifteen (15) program managers the ARPA-H hired as of May 2024, none is aligned to the Proactive Health focus area, which represents the highest payoff in the form of cost avoidance due to low literacies, unhealthful habitats, harmful lifestyle choices resulting in preventive, chronic, noncommunicable diseases (comorbidities), presenteeism, underperformance, and even premature death. The ARPA-H programs increase technologies readiness for treating diagnosed diseases of modernity and genetic mutations. While the ARPA-H fills a narrow gap of high-risk acquisition that the National Institutes of Health (NIH) and the National Science Foundation (NSF) do not cover, its programs' objectives focus more on disease management and the biological understanding of diseases. It is still at the level of digital modeling and digital simulations at the cellular or tissue levels, rather than at the whole human level. ARPA-H does have a Proactive Health Office and it released its innovative solutions openings solicitation in May 2024 (ARPA-H, 2024). Its low/no-cost sensing modalities focus on early detection of diseases and illnesses. It is unclear that such sensing modalities are for human digital modeling, simulation, or twinning.

The National Academies of Sciences, Engineering, and Medicine (NASEM) release a consensus study report entitled Foundational Research Gaps and Future Directions for Digital Twins in December 2023 that spanned human biology, ecology, and engineered systems. The report enumerated 48 gaps, 22 findings, 19 conclusions, and eight (8) recommendations after information gathering via sessions, domain-specific and

public workshops. The three public workshops were in biomedical sciences, atmospheric, climate, and sustainability sciences, and engineering domains. The National Academy of Medicine has published a discussion paper on digital health extensively (Abernethy, et. al., 2022).

As mentioned earlier, NASEM (2023) defines digital twin and emphasizes that the bidirectional interaction between the virtual and the physical is central to the digital twin. It also emphasized that a digital twin is more than just digital modeling or simulation. NASEM recommended an enterprise architecture be created by articulating a need for an integrated research agenda, launching cross-cutting programs, and establishing an interagency working group. The NASEM highlighted a foundational gap of trust in DTs that methods to continually verify, validate, and uncertainty quantification (VVUQ) could mitigate.

Another NASEM recommendation is to provide researchers with computational resources. NASEM looked past the human potential to recommend all humans be self-scientists who model and simulate themselves along the continuum of anatomy, physiology, psychology, sociology, and ecology. NASEM regard all humans hold the energetic states that mathematical theory and algorithms have not describe with the aid of instrumentation so educating, training, and equipping all humans with foundational scientific skills, devices, and computing resources for human digital twinning will shorten the time to discover missing theory and algorithms. NASEM findings and recommendations also presume that the solutions to the hardest biomedical problems of health restoration to performance optimization will be solved by scientists but not self-scientists.

Notably, no US Surgeon General has broached the topic of the HDT through its office's publications types—Call for Action, Advisory, or Workshop Report. The Department of HHS (DHHS) is in its fifth decade of the Healthy People program but the data and information that program aggregates and creates associated with a HDT are in the context of disease and healthcare providers as the primary user because the simulations require high performance computing (ODPHP, 2024).

In 2011, the United States' Department of Defense (DoD) established Total Force Fitness (TFF) in order to understand, assess, and maintain the fitness of the warfighter (Travis & Brown, 2023). The TFF framework is inclusive of servicemembers' dependents, communities, and organizations meaning a population of more than 11 million, where fewer than two (2) million are service members. The military health system (MHS) moved away from its disease care model or "come to the Military Treatment Facility" to a holistic care model because the 2017-2019 National Defense Authorization Act mandated it. The Joint Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities, Policy Change Recommendation (DCR) for TFF is based on an April 2017 capabilities-based assessment (CBA) of the TFF.

According to the CBA report, the U.S. DoD was uncoordinated in delivering TFF services, could not quantify TFF impact on mission readiness or effectiveness because of its siloed processes of data collection, standards, and infrastructure. The 28 actions the Joint Requirements Oversight Council directed be implemented to mitigate gaps in the CBA report and DCR have not been mitigated. Travis & Brown (2023) proposed a robust health information technology (HIT) system to support all capabilities. They also proposed nine requirements for the MHS.

The Consortium for Health and Military Performance (CHAMP) (2024) is the go-to resource for evidence-based information on human performance optimization to improve the performance and resilience of Military Service Members and their families. There are eight domains of TFF—physical, environmental, medical and dental, nutritional, spiritual, psychological, behavioral, and social fitness. Unfortunately, the

human performance resources by CHAMP do not have any intent to use HDTs for communicative ways to maximize performance, fitness, wellness, and nutrition.

The Whole Health (WH) System of Care is the Veterans Health Administration (VHA) transformational goal (Anderson et al., 2023). The VHA serves nearly twenty (20) million eligible military veterans and their family members. So, like the MHS, the VHA has purview of human healthcare from lust-to-dust, where supercentenarians are patients.

Like the MHS reforms and the CHAMP communication mechanisms, the WH Clinical Care element of the WH System of Care does not include any intent for HDTs to support its primary and specialty cares services offered. All four of the WH principles for approaching clinical encounters—the state of the Veteran's Health and well-being is assessed in a comprehensive, whole-person way; what matters most to the Veteran-their meaning or purpose in life-is elicited early and prioritized throughout the encounter; the Veteran is supported in setting and pursing realistic health and well-being goals that are related to what matters most to them; and the Veteran is equipped with knowledge, information, and resources in support of these goals, are ideal HDT use cases despite occurring in a clinical setting.

Anderson et al. (2023) conducted a qualitative study based on 25 interviews of healthcare professionals across disciplines and services at a VA Medical Center in 2020-2021, including chaplains, pulmonologists, primary care providers, and palliative care providers. The key results are grouped into four areas of concerns —the appropriate depth/breath of inquiry in person-centered assessment; the rationale for elicitation of what really matters; the feasibility and appropriate division of labor in personal health goal setting and planning; and challenges related to referring Veterans to a broad spectrum of supportive services (Anderson et al., 2023). Each concern traces to an intrinsic feature of HDT as being always ready to collect data, transform data, and communicate information with its physical asset.

Human Digital Twin – European Initiatives

On December 21, 2023, the Virtual Human Twin (VHT) launched alongside the announcement of the European VHT Initiative, facilitated by the European Digital Twins in Healthcare (EDITH) Coordination and Support Action (CSA) and Virtual Physiological Human (VPH) (European Commission, 2023). The potential for VHTs to contribute deep understanding of physiology, pathology, and disease etiology, as well as facilitate personalized, patient-centric medicine is substantial according to the EU commission.

The EU commission's (2023) goal is advanced VHT-based solutions in health and care enabled by pooling resources and assets to further develop the requisite science and technology. These declarations mean the EU commission's paradigm for health and care, like the United States, is devoid of the tantamount conditions in food supplies or stuffs and humans' habitat imperfections—contaminants, pollutants, toxicants, poisons, irritants, etc.

Their focus on the harmful effects of unhealthful habitats or environments on the mind and body coupled with those of a western lifestyle—excessive consumption of ultra-processed foods of low nutritional value, lower volumes of less intense movement, too much time indoors, junk light, less time outdoors, loneliness, poor sleep, and chronic stress demand a high-frequency and life course strategy of data collection suited for human digital twinning. Co-requisite to this strategy is lifelong scientific education and evidence-driven training of each human so they never become a patient of preventive diseases.

Discussions

Human Digital Twin – Comparison of Initiatives

Since the majority of the past and present HDT technological development is tied to advances in medical devices and pharmaceuticals, it follows that the United States and the European Union are attributable for nearly all the progress in human digital models, human digital shadows, and HDT research and development. This is largely due to the fact that the U.S. and the European countries have led research and development in supercomputers, software, and diseased/injured/disabled humans.

Examining the national and international initiatives led by the U.S. and the European Commission shows that the global team for HDT is still in the forming stage. Teams focused on either pre-injury and disease or post injury and disease HDT applications. For instance, The VHGS 2023 community, like the EU commission, only discussed pathophysiology use cases for HDTs and did not explore modeling human environments which is import to the proper mechanistic and stochastic multiscale modeling of human physiology and cellular biology.

The salient suggestions in the draft VHGS report include the importance of patient engagement and participation in the development of digital models but not ownership of them, the creation of a framework from which to develop patient baseline information that is expected to be integral to future digital twin solutions (VHGS Committee, 2024). The VHGS committee and Lauer-Schmaltz et al (2024) perspective match as illustrated in Figure 2.

Another commonality in HDT initiatives is human performance professionals and medical teams as the primary users. At some point in the near future, the human should be the primary user of its HDT over its life course if HDT deployment will scale to laypeople. Moreover, in a century's time, laypeople will be far more informed and smarter at optimizing their biology and controlling their environments because of the empowerment from human digital twinning throughout their life course.

There are areas of alignment in certain initiatives despite of using different terms. For instance, the U.S. DoD TFF domains and WHS research areas are comparable. The U.S. DoD TFF program identified eight domains and the Veterans Health Administration's Whole-Person Health System (WHS) identified several research areas (Deuster, 2023; Anderson et al., 2023). The TFF eight domains are physical, social, psychological, environmental, nutritional, financial, spiritual, and medical (Deuster, 2023). The WHS identified physical, behavioral, spiritual, and biological research areas that clinicians integrate germane scientific discoveries into revised standards and qualities of care which translate into coordinated care for veterans and their families (Anderson et al., 2023). Although there is a lacking of specifically targeted HDT initiatives, DoD TFF and VHA WHS provide perspectives and requirement domains/areas for HDT design and development.

Major stakeholders involve researchers, developers, leaders, and program managers germane to the domains and research areas, and determinants of health, fitness and performance. The DoD has the personnel for performance optimization and the VHA employs the disease prevention professionals who have the organizational knowledge and holistic service delivery experience.

There are areas for improvement in certain initiatives. For instance, although the HIT system proposed by Travis and Brown (2023) include requirements that are aligned with TFF initiatives, it did not include HDTs as endpoints. They recognize a high-level construct that satisfies the TFF framework and organizes the MHS to satisfy the NDAA requirement. But how to deliver optimized human performance remains to be

generated. Enterprise architecture helps serve such a purpose but Travis & Brown (2023) did not use or acknowledge the discipline of model-based system architecture.

The other impetus for these developments is the minimization of an asset's life cycle cost. In management of portfolios, programs, and projects, there is a saying of "fast, cheap, good; pick two because you can't have all three." And the triple constraint — schedule, cost, and performance verify this truism. The quest for the human digital twin is subject to this iron triangle as well.

The scope of HDT roadmaps is the life course while the scale spans subcellular to the human body and mind. The current programs and products from the initiatives are not intended for the layperson over the life course; HDT implementations are built for human performance or medical professionals. For example, Travis & Brown (2023) did not consider the service member to become a self-scientist who narrows knowledge gaps between caregivers in the MHS during a military career.

The US government, unlike the EU, does not have a human health and services capability assessment for optimal living with expert-validated gaps, rationalizing capability requirements resembling the HDT for scientist and self-scientists to configure, own, operate, administer, and secure digital twins. There are also tremendous challenges for HDT system to be interoperable with the medical industrial complex's electronic health record systems – despite two decades of US government appropriations and rulemaking, they are not fully interoperable (e.g., fax machines are task critical equipment for some communications).

Besides transitions through other phases of team development by strategic alignment with nominal instruments of commitment and procurement, the social and technical challenges ahead are significant to eventually deploy HDT for all humans. Progress should continue in networking sensors, rendering data in multiple modalities, and integrating mechanistic and statistical models across disciplines and scales.

Some academic research shows promise of filling the gaps called out by the initiatives. For instance, Davila-Gonzalez and Martin (2022) have digitally modeled humans in the context of industry 5.0. Javaid et. al. (2022) studied medical sensors and wireless communications in support of digital health. Laamarti et. al. (2020) discussed standardization issues of human digital twins in smart cities (i.e., digital twin of cities).

Conclusion

The U.S., EU, and international organizations are developing human digital twin programs through various initiatives. Despite different initiatives, they aim to coordinate, collaborate, and integrate capabilities that empower licensed and certified professionals first and foremost, the laypeople second. The negative trends in the incidence and prevalence of diseases, disorders, and injuries are the impetuses for HDT development.

While consensus on future directions emerges with national and international collaborations, gaps in foundational knowledge of human biology and how to best digitize such knowledge remain. The findings in this research are useful for information system architects and designers to understand the requirements for developing fit for purpose HDTs. The value propositions for HDT technology investments are to reduce healthcare costs and improve quality of healthcare. There should also be a value proposition for HDT to improve well-being of humans and quality of life.

Hence, in addition to the extant initiatives, there should also be a call for scope expansion and putting human digital twins into the hands of all humans. To fulfill a vision of human digital twin spanning the life

course of a century or more and human's lifelong education, fitness, and performance enabled by its HDT requires strategic and innovative initiatives that have not yet rolled out.

There is an obligation to apply some of the intellectual capital and computing capacity that facilitate environmental preservation/conservation/destruction and humans' quality of life in their life course to address the double-edged consequences of modernity by preventing disease, predicting symptoms, treating root causes, and educating humans (not only patients and caregivers) efficiently and effectively with HDT-equipped healthcare (vs. disease-care) systems.

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