INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.132

Designing Human Digital Twins for Behaviour-Changing Therapy and Rehabilitation: A Systematic Review

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Abstract

One of the most promising trends in healthcare digitalisation is the personalisation and individualisation of therapy based on virtual representations of the human body through Human Digital Twins (HDTs). Despite the growing number of articles on HDTs, to-date no consensus on how to design such systems exists. A systematic literature review for designing HDTs used for behaviour-changing therapy and rehabilitation resulted in eight key design considerations across four themes: regulatory and ethical, transparency and trust, dynamism and flexibility, and behaviour and cognitive mechanisms.

Keywords: digital twin, human digital twin, healthcare design, human-centred design, behavioural design

1. Introduction

The increasing significance of digitalisation, together with trends such as the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI), holds great potential, not only for industry, but also for other domains such as healthcare and therapy. Due to the aging society, rehabilitation of diseases like stroke plays an increasing role in healthcare, resulting in a huge demand for new rehabilitation and therapy methods. One of the most promising trends in this direction is the personalisation and individualisation of therapy, care, and medication based on data-driven virtual representations of the human body, Human Digital Twins (HDTs, in healthcare also sometimes referred to as patient digital twins) (Barricelli *et al.*, 2019; Patou and Maier, 2017). However, despite the growing number of articles discussing HDTs and their potential future impact, there is no current consensus on how to design such systems.

HDTs are currently defined as *"computer models of humans tailored to any patient to allow researchers and clinicians to monitor the patient's health, for providing and test treatment protocols"* (Barricelli et al., 2020, pp. 2). Specifically, this means that physical, biological, and historical data is used to monitor the patient's health and behaviour and contribute to fast and reliable decision-making during therapy (Liu *et al.*, 2019; de Maeyer and Markopoulos, 2020), resulting in a shift from a "one-size-fits-all" principle towards tailored-made treatments (Barricelli *et al.*, 2019). As such, in addition to physiological applications (e.g. musculoskeletal, Pizzolato et al., 2019), HDTs have the potential to go beyond the above definition to include behaviour-related information and feedback and therefore tackle behaviour-changing interventions such as motivation and identity. However, while there is lots of research done already in other major technology domains such as manufacturing or aviation, there are currently no specific frameworks for the design of HDTs particularly in the field of behaviour-changing therapy and rehabilitation (Barricelli *et al.*, 2019). This is a major challenge, since such HDTs differ from conventional digital twins used in, for example, industrial applications but also from HDTs in solely

physiological therapy applications in a number of ways. As such, there is a critical need to identify the major considerations specific to HDT design in behaviour-changing therapy and rehabilitation.
Given this need, the aim of this paper is to answer the research question on which key design considerations based on current literature addressing HDT application need to be considered for behaviour-changing therapy and rehabilitation as well as to provide a general framework for the design of HDTs in behaviour-changing therapies and rehabilitation.

2. Theoretical Background

A digital twin in general can be defined as *"(…) a digital representation of an entity, including attributes and behaviours, sufficient to meet the requirements of a set of use cases, that is, they are virtual representations of physical assets"* (Angulo et al., 2020, pp. 3). Digital twins consist of three major components: a physical object, a corresponding virtual object, and a continuous bi-directional data stream for transferring data from the user to the system and feedback from the system back to the user (Barricelli *et al.*, 2019). Accompanying its physical equivalent over its whole lifecycle the digital twin offers all users and stakeholders the possibility to access and monitor the physical twin's status, control and optimise its processes, and enable simulation and testing (Barricelli *et al.*, 2019).
Currently the design of digital twins is based on whether the digital twin is data-based or system-based. Data-based digital twins aim at creating a data structure out of sensor data and other information to give an overview of the current state of a system and provide the possibility of analysis, simulation, and prediction of future events or states. Here common design features include a collection of relevant data that are stored inside a database as well as corresponding models, analyses, and functions connected to those data. In contrast, system-based digital twins aim to virtualise an actual physical object itself. Therefore, the corresponding design features include a description of logical links and relationships of the object's components, precise models of each component generated with tools like CAD or CAE, and their parameterization based on relevant sensor data (Adamenko *et al.*, 2020).
HDTs in therapy and rehabilitation substantially extend the scope and nature of digital twin applications (Saddik, 2018), such that the human patient is seen as the physical object, which is monitored and based on whose data simulations should be done to predict and improve the treatment's outcome (Barricelli *et al.*, 2020). However, due to the complexity introduced by integrating, for example, cognitive and social mechanisms, the human object brings substantial additional requirements and challenges for the design of HDTs. For instance, in contrast to digital twins in other domains, HDTs are usually not continuously connected to their physical twin as the human body does not include integrated sensors, which can lead to data gaps and thus may result in wrong decisions (Barricelli *et al.*, 2020). Moreover, because the data is patient-related, data privacy and security play an even more critical role than, for example, in the industrial domain (de Maeyer and Markopoulos, 2020). Finally, especially in the field of behaviour-changing therapy and rehabilitation, human factors, such as human's physiological and cognitive state, as well as psychological factors, such as motivation and trust, become increasingly important (de Maeyer and Markopoulos, 2020; Petrova-Antonova *et al.*, 2020). Behaviour-changing therapy and rehabilitation in this case describes any form of therapy that aims at helping the individual to change their behaviour in a certain way to improve their health state using behaviour change techniques like, for instance, using self-monitoring of the patient's behaviour and giving feedback on their performance (Michie et al., 2011). Thus, considerations from traditional digital twin design must be revaluated in the context of HDT especially in behaviour-changing therapy and rehabilitation.

3. Methodology

Given the lack of literature-informed guidance about HDTs in behaviour-changing therapy and rehabilitation as well as the limited number of current real-world examples, it is necessary to bring together understanding about HDT design from across literatures as an essential foundation for further work. Thus, a systematic literature review was conducted following the updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement consisting of three main phases (1) Identification, (2) Screening, and (3) Inclusion (Page *et al.*, 2021), as summarised in Figure 1.

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In order to distil insights from across literatures the search was conducted through three databases: two of the most prominent multi-disciplinary databases Scopus and Web of Science, and the biomedicine- and health-specific database PubMED. To ensure an inclusive yet focused literature search, first, a general search for digital twin in healthcare was conducted using a combination of two categories of keywords to construct the search terms: (1) DT related keywords, and (2) healthcare related keywords. Based on the resulting collection of records, those without mentioning HDTs for behaviour-changing therapy and rehabilitation purposes or those that focused on a specific illness or treatment method were filtered out. To-date, the term digital twin is used broadly in literature and definitions vary (Barricelli et al., 2019). Only records explicitly mention HDTs were considered and selected in the scope of this review. Hence, the remaining 19 papers were included in this review for further analysis.
To address our research question mentioned earlier, we reviewed the included papers for key design considerations in the design of HDTs, that arise from applying the concept of digital twins to a human patient in a behaviour-changing context.

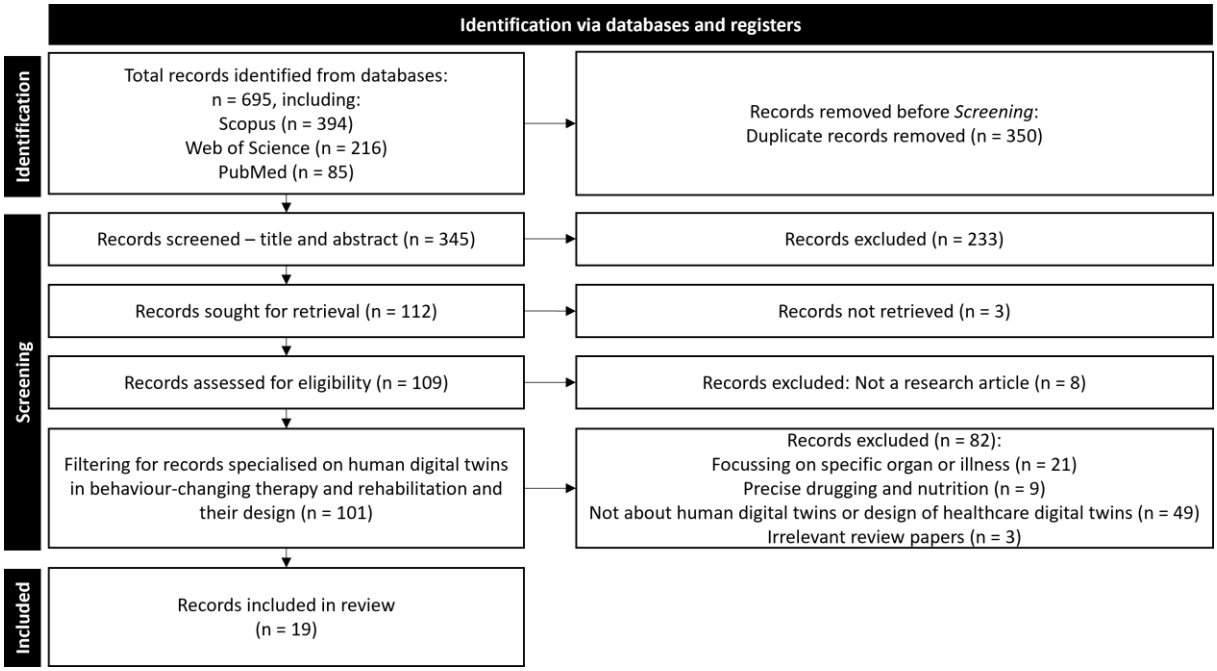

Figure 1. PRISMA diagram summarising the systematic literature review of human digital twins (HDTs) in behaviour-changing therapy and rehabilitation

4. Results

In the following, first a descriptive overview of the included papers and their contents is given. Subsequently, these records are analytically reviewed for the main design considerations in HDT design.

4.1. Overview of relevant recent work

From the initial set of 695 records, a total of 19 research articles (five conference papers and three journal papers from 2019 as well as six conference papers and five journal papers from 2020) were relevant to the research question. As such, the emergence of Human Digital Twins (HDT) as a major topic is recent, in contrast to the first mention of digital twins in 2002 (Grieves and Vickers, 2017), and poses substantial scope for further research. The growth of HDTs as an important theme with substantial unanswered research questions was also highlighted by a number of review papers identified, for example, in this work (Barricelli *et al.*, 2019; |Erol *et al.*, 2020a, 2020b; Fuller *et al.*, 2020). Table 1 provides an overview of the records reviewed in this paper in terms of their year of publication, publication type (C = conference, J = journal), and content.

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Table 1. Overview of the reviewed papers and their content

Paper	Year	Type	Summary
(Angulo *et al.*, 2019)	2019	C	Proposal of basic considerations for digital twins in health care
(Liu *et al.*, 2019)	2019	J	Implementation of an HDT-based framework for elderly care
(Comito *et al.*, 2019)	2019	C	Framework proposal for a clinical decision support system that includes a digital patient, based on various patient data
(Hafez, 2019)	2019	C	Case study of Human-AI-Alignment within a HDT-based smart environment
(Rivera *et al.*, 2019)	2019	C	Framework proposal for building a HDT for healthcare and precision medicine
(Abeydeera *et al.*, 2019)	2019	C	Introduction of Smart Mirror - a system that supports everyday life and well-being using a HDT integrated into a mirror
(Barricelli *et al.*, 2019)	2019	J	Review of digital twins in general with definitions, current application domains and design requirements
(Pizzolato *et al.*, 2019)	2019	J	Review of how to combine multiple stimulation approaches with a detailed musculoskeletal digital twin for rehabilitation of spinal cord injury patients
(Erol *et al.*, 2020b)	2020	C	Review of recent work on digital twins in different domains
(Lutze, 2020)	2020	C	Concept proposal for digital twin-based information management systems in health and medical software products
(Fuller *et al.*, 2020)	2020	C	Review of digital twins in different domains
(Erol *et al.*, 2020a)	2020	C	Review of digital twins in different healthcare domains
(de Maeyer and Markopoulos, 2020)	2020	C	Interview-based study on perception, requirements, chances, and risks of HDT in elderly care
(Petrova-Antonova *et al.*, 2020)	2020	C	Concept proposal for the HDT-based exploration of behavioural changes of patients with cognitive disorders throughout Multiple Sclerosis therapy
(Mohapatra and Bose, 2020)	2020	J	Review- and case study-based framework proposal for digital twins in healthcare
(Gámez Díaz *et al.*, 2020)	2020	J	Review of HDT-based coaching systems and their requirements
(Laamarti *et al.*, 2020)	2020	J	Framework proposal for an ISO/IEEE 11073 standardised HDT for health and well-being
(Calderita *et al.*, 2020)	2020	J	Design proposal of a CORTEX-based cyber-physical system for ambient assisted living
(Barricelli *et al.*, 2020)	2020	J	Introduction of SmartFit - a HDT-based coaching system for monitoring athletes and suggesting improvements

4.2. Distilling key design considerations of HDTs

Several HDT design considerations emerge from the literature, which go substantially beyond the typical components of a digital twin (i.e. a bi-directional data connection using communication standards such as ISO/IEEE 11073 (Laamarti *et al.*, 2020), data storage and processing unit, data-analysing and simulation tools, and user interface).

Regulation and ethical considerations

The first important consideration is *identifiability and traceability*. In this context, this means that the HDT must be clearly assignable with respect to its associated patient and that substantial changes in the underlying implementation must be traceable (Lutze, 2020). Since the decision-making in HDT-driven therapy is based on the patient's personal data, confusing those data would result in severe consequences not only for the therapy's effectiveness but also for the patient's health. Besides being required by regulation, such as the EU Unique Device Identification system guidelines (Lutze, 2020), assigning each HDT a unique identification number (ID) is one way to prevent such confusion. Further, as elaborated below, therapy applications are highly dynamic systems. Changes in the patient's condition, alterations in the group of people involved, and changing regulation often require substantial adjustments in the

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implementation and design of the HDT. This makes versioning both important and particularly challenging in the context of an evolving HDT.

Established regulation, such as the General Data Protection Regulation (GPDR), often concern *security and privacy* since personal and medical data are highly sensitive and theft or abuse of those data could cause severe damage to patients (Barricelli *et al.*, 2019; Gámez Díaz *et al.*, 2020). The interviews by de Maeyer and Markopoulos (2020) reveal that most patients would be worried if their medical data didn't stay secured within a hospital or the general practitioner and would only want to share them with medical staff and stakeholders directly relevant to the therapy. Further, with respect to the growing importance of data privacy and ownership, ethical questions such as what should happen to the HDT and the associated data in the event of an (unexpected) termination of therapy arise. The majority of respondents in de Maeyer and Markopoulos (2020), for instance, state that their HDT should be deleted in the event of their death while others could imagine making their data available to contribute to the further success of the system. Therefore, data protection as well as data privacy and ownership take on a particular priority in the design of HDTs and are critically related to trust in the system.

Transparency and trust

Trust plays a major role in HDT therapy, as it determines the extent to which the patient voluntarily engages with the system and thus allows the HDT to improve therapy outcomes (Lee and Lin, 2011). Similar to traditional digital twins, HDTs integrate three-layers consisting of data collection, data storage and processing, and a user interface providing feedback, visualization, and other information to different user groups. However, issues in any one of these three layers can shatter trust in the system.

In the data collection layer, a key challenge is obtaining *quality and consistency* within the collected data as this is the foundation for reliable decision making and therefore for the trust put in the decisions by the patient and professionals. While noise-free and continuously captured data is crucial for digital twins to provide trustworthy decisions, as already stated in Section 2, HDTs usually don't perceive continuous data, which can result in data gaps and inconsistencies (Barricelli *et al.*, 2020; Fuller *et al.*, 2020). Further, manually inserted data, for example by the user or by other involved stakeholders such as family, can be corrupted as people might not be qualified to handle the data correctly, confuse data or simply forget to input them (Laamarti *et al.*, 2020). Such issues can result in severe consequences for the personal health such as insufficient therapy results or even injuries due to wrong treatment, as well as damaging trust in the accuracy of the HDT. This places a number of substantial design demands on HDTs needing to deal with potentially incomplete or unreliable data from varied sources.

In the data storage and processing layer, *explainability and understandability* regarding the source of decisions is important. Digital recommendation systems often suffer from a "black box" nature making the resulting decisions for non-experts incomprehensible and non-transparent (Barricelli *et al.*, 2020). Further, especially when it comes to AI-based systems, many people build up a high degree of scepticism, on the one hand due to the high complexity and on the other hand due to the still prevailing fear of some people that AI systems could surpass humanity at some point in the future (Fuller *et al.*, 2020). To overcome this, Fuller et al. (2020) suggests explaining the HDT system as well as the resulting benefits to the user at a foundational level, while Laamarti et al. (2020) points out that appropriate data visualization can help users understand the underlying data and its processing. Further, the AI system requires expert training as well as extensive validation, introducing further potential barriers to trust, not least in the potential reliance on various experts (Barricelli *et al.*, 2020; Fuller *et al.*, 2020). Thus, HDTs introduce substantial additional trust issues in the interaction between user and data processing.

Finally, the user interface layer has the potential to support or undermine trust in the other layers depending on its user friendliness regarding *simplicity and intuition*. In any application, a poor user interface can result in confusion and frustration. However, this takes on particular significance in the context of HDTs where a user is potentially observing a 'twin' of themselves, needs to understand and enact potentially health critical rehabilitation feedback, and could also have cognitive impairments or other challenges associated with key use cases such as elderly care or stroke therapy. Here de Maeyer and Markopoulos (2020) stress the key role of simplicity, pointing out that the user interface should be designed in an as intuitive and understandable way as possible. Thus, HDTs face critical challenges in maintaining simplicity and intuitiveness while providing appropriate personal feedback.

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Dynamism and flexibility

Due to the evolving nature of HDTs there is a critical focus in both their function and design on *flexibility and adaptability*. Humans and their environments can be seen as dynamic systems that are undergoing permanent change. In the therapy context, this manifests primarily in changes in the patient's condition, associated changes in professionals and stakeholders, for example when family members, new therapists or other medical staff need to be involved, and even a changing context, for example when new diseases emerge. Correspondingly, this implies the need for ongoing adaptation of the HDT to the patient's current condition through continuous learning techniques (Gámez Díaz *et al.*, 2020). Here, past information about the patient's development and behaviour as well as new data are fused to continuously retrain the underlying AI model and thus ensure appropriate predictions and decisions as well as the essential verisimilitude in the HDT itself (Barricelli *et al.*, 2019; Gámez Díaz *et al.*, 2020). In addition, new regulation can be introduced at any time, making flexibility crucial not only within the HDT itself but also within the whole design process. Based on this Lutze (2020) criticises the commonly used "V-model" in medical software development as too rigid for the HDT context. Instead, Lutze (2020) propose an extended V-model using agile methods to add flexibility to the design process and allow the designer to dynamically make adjustments in terms of system specification, component design, implementation and specifications across the changing life cycle of the HDT. As such, HDTs demand high flexibility in their design and design process to incorporate emerging aspects at each stage of development and autonomously adapt to changes in circumstances during operation, ensuring maximum accuracy throughout the HDT's entire lifecycle.

Behaviour and cognitive considerations

Finally, the biggest difference between HDTs and digital twins, is the focus on human factors. In addition to factors such as the human's physiological aspects, particularly in behaviour-changing therapy and rehabilitation the user's cognitive mechanisms are central to both the HDT and its impact on the user. Despite this importance, there has been a general focus on technical implementation (potentially attributable to the emerging nature of HDTs in the literature) and thus few records have focused on such considerations. Notably, Petrova-Antonova et al. (2020) highlight how information about the development of important cognitive capabilities such as information processing, memory, expressive language, and executive function throughout therapy can be crucial for decision making especially in rehabilitation of patients with cognitive disorders. This points to a wide scope of behavioural and cognitive mechanisms that must be considered when dealing with HDTs. In this context, only motivation has been discussed to any degree in the reviewed literature, highlighting a substantial research gap.

In the context of this limited discussion, there has been a general focus on the HDT providing a unique platform for improving *motivation and support* through behaviour changing feedback, eventually even embodied in a virtual twin of the patient itself. In particular, de Maeyer and Markopoulos (2020) especially highlight the possibility of self-design and better self-discipline in HDT-based therapy. Here, self-design describes how a HDT could support motivation by tracking and visualising the patient's progress while self-discipline refers to motivation resulting from increased goal orientation through reminders and reward according to the patient's individual habits and desires (Gimpel *et al.*, 2013). Such feedback could for instance be directly visualised on an embodiment of the HDT while being supported by audio or haptic channels, e.g. the control of an exoskeleton supporting the patient during therapy, all coordinated by the HDT considering both information about the specific user (e.g. the patient or therapist) and the given context (e.g. hospital or home). Hence, despite limited discussion, it is apparent that HDTs necessitate a number of specific considerations in their delivery of behaviour changing feedback to trigger cognitive factors such as motivation.

As hinted before, central to these considerations is the *conceptualization and* potential *embodiment* of the HDT into a human-like virtual or physical object. De Maeyer and Markopoulos (2020) reveal that most patients associate HDTs with a collection of data stored on a database and linked to algorithms. However, one of the interviewees also showed skepticism about whether such a construct would positively contribute to trust and motivation (de Maeyer and Markopoulos, 2020). Incorporating the HDT into a virtual or physical human-like object, eventually even with respect to the look of the user themselves, could make the underlying concept more graspable and intuitive and possibly even enable the establishment of a bond

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between the patient and the HDT. For example, de Maeyer and Markopoulos (2020) explain how an HDT could be incorporated into a robot that could serve as a personal companion for the patient. Abeydeera et al. (2019) go one step further and integrate the HDT into an intelligent mirror system, which is intended to serve the user as a companion and advisor for well-being and everyday tasks. Through the combination of the HDT and the patient's mirror image, behaviour-changing through identity shaping can thus be more intensively triggered. Thus, the embodiment of HDTs introduces a number of design options for behaviour change by making feedback more personal, understandable and responsive.

5. Discussion

Bringing the results of the review together, we distilled eight key considerations emerging from the nascent research on HDTs. These considerations as well as the themes they can be assigned to are summarised in Table 2.

Table 2. Eight key considerations for the design of Human Digital Twins (HDTs) in behaviour-changing therapy and rehabilitation

Consideration	Description
Regulatory and ethical considerations	
1) Identifiability and traceability	Using unique identifiers and versioning allows to clearly assign the HDT to its physical counterpart as well as providing traceability over substantial changes.
2) Security and privacy	Data security and privacy as well as data ownership must be priority in every layer of the HDT due to the high sensitivity of personal and medical data.
Transparency and trust	
3) Quality and consistency	High data quality and consistency is crucial for a reliable and trustworthy decision making, resulting in design demands for handling inconsistent and unreliable data.
4) Explainability and understandability	AI-based decision making bears a demand to overcome associated trust issues raised by high complexity and expert dependency.
5) Simplicity and intuition	Simple and intuitive designed to prevent frustration and discouragement when interacting with the HDT.
Dynamism and Flexibility	
6) Flexibility and adaptability	The high dynamism of humans and their environments requires a highly flexible design process as well as the HDT itself being continuously adaptable throughout its operational phase.
Behaviour and cognitive mechanisms	
7) Motivation and support	Providing adequate behaviour changing feedback can be a powerful tool to improve motivation and therapy support.
8) Conceptualization and embodiment	Conceptualizing the HDT itself as a visual or physical appearance can make the underlying concept more tangible and possibly even lead to a bond between patient and HDT.

Further, the considerations as well as their impact on the general conceptualisation of HDTs in behaviour-changing therapy and rehabilitation is illustrated in Figure 2. While most of the considerations can also be found to some extent in conventional digital twin frameworks, their role goes far beyond this in the context of an HDT due to the human-specific factors. For example, Adamenko et al. (2020) also highlights the importance of high data quality and consistency in the context of industrial digital twins, emphasising that decreasing data reliability would imply a decrease in value of the digital twin to the company. In contrast, as discussed in detail in Section 4, data uncertainty in the context of HDTs in therapy or rehabilitation applications emerges from a number of distinct sources and can lead directly to severe consequences for the patient's health. This shows that applying the digital twin concept to humans, especially in the medical context, leads to a shift in the significance of some traditional considerations, as well as the introduction of totally new considerations. As such, we highlight the distinctive considerations in red in Figure 2.

As shown in Figure 2, HDTs also imply entirely new considerations compared to digital twins in other domains. Behaviour mechanisms such as trust and motivation, for example, cannot be found in machines or processes but are crucial for the success of therapies and rehabilitation of human patients (Lee and

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Lin, 2011; de Maeyer and Markopoulos, 2020). Therefore, such new mechanisms must also be inserted into the design of an HDT, which may lead to correlations with other considerations of the framework.

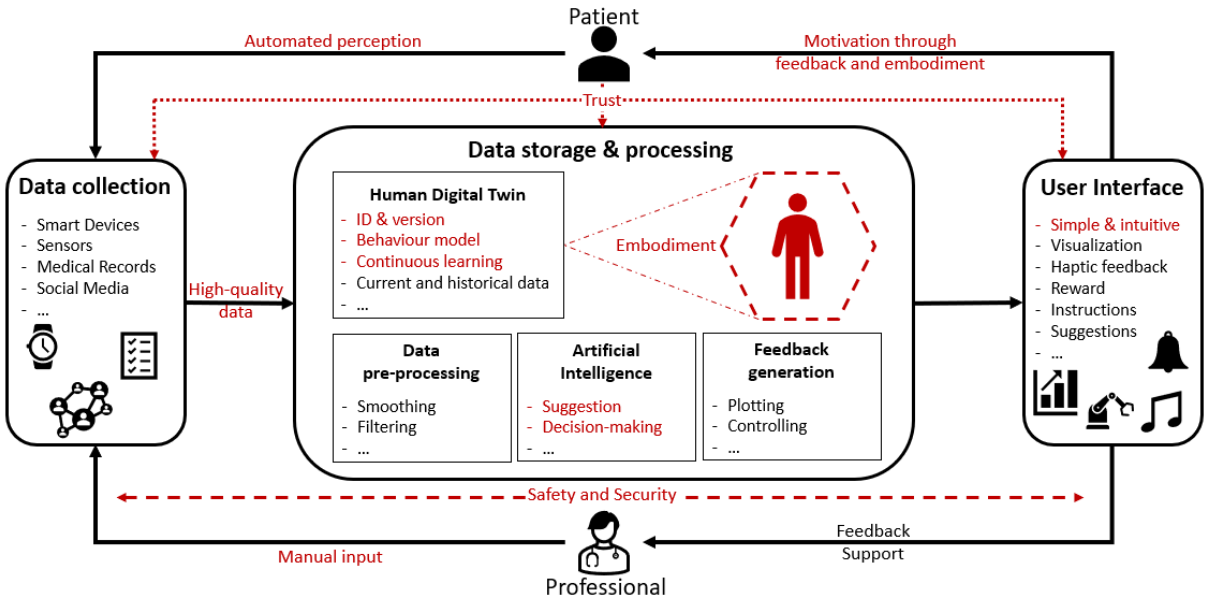

Figure 2. Human Digital Twin framework with key considerations (red) beyond those typically associated with digital twin design in general

For example, an embodiment of the HDT, which in industrial applications can usually be found e.g. in the form of CAD or CAE models used for purely illustrative or simulation purposes, can, in case of therapy, encourage the patient's personal identification with their HDT (Abeydeera *et al.*, 2019), which in turn can improve motivation and impact other considerations such as trust.

The considerations distilled in Table 2 and illustrated as part of a HDT in Figure 2 further provide a basis for a number of theoretical and practical implications and directions for further work.

Starting with the question of what a HDT actually is, our results provide a first step towards connecting conceptualisations of HDTs to concrete design considerations. However, the lack of more fully developed definitions, conceptualisation or operationalised design guidelines highlights the need for further research in the definition of HDTs, their essential components, and how these should best be addressed by designers. Further, especially in the field of behaviour-changing therapy and rehabilitation, our work highlights a critical interaction between HDTs and behavioural mechanisms. However, to date, only trust and motivation have been touched on in the reviewed literature. As such, these primarily serve to highlight the substantial gap between current understanding of HDTs and how they might interact with the more complex models of behaviour change prevalent in the behavioural science and behavioural design literatures (Bay Brix Nielsen *et al.*, 2021). Overall, the results highlight a number of directions for further conceptualisation of HDTs and their design.

In addition to these theoretical directions, our work points to two main implications for designers developing a HDT. First, while Table 2 is, to the authors' knowledge, the first set of HDT design considerations, these can only provide an initial insight, highlighting key areas of attention. They do not provide a fixed guideline for the design of HDTs. As such, the developer should always keep track of the specific use case of the desired application, as there could be deviations in impact or relevance of some of the aforementioned considerations in specific contexts. In some use cases, for instance, it may be advantageous to provide not only professionals, but also caregivers and relatives access to parts of the HDT. For all use cases, there should be a consideration of delimitation, i.e. what data not to include. Second, as discussed in the results, flexibility during the development process can be crucial for adapting to contextual changes, and accounting for the evolving relationships highlighted in Figure 2. Since the ultimate goal of HDTs in behaviour-changing therapy and rehabilitation is to achieve best possible results, such flexibility should be ensured in all development stages, for example, by enabling iterations between them, as well as in the HDT lifecycle.

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6. Conclusion

We set out to distil key design considerations in the design of HDTs in behaviour-changing therapy and rehabilitation. To this end a systematic review of 695 records was conducted, resulting in a focused review of 19 records related to human digital twins (HDT) in different kinds of therapies. Based on this, we identified how HDTs substantially differ from traditional digital twins and introduce a number of additional design requirements. Specifically, we distilled eight key considerations associated with four themes: Regulatory and ethical considerations, transparency and trust, dynamism and flexibility, and behaviour and cognitive mechanisms (Table 2). These also formed a basis for elaborating the general understanding of digital twins to highlight how HDTs differ structurally, as illustrated in Figure 2. Together the identified considerations provide the basis for a number of theoretical and practical implications surrounding research and implementation of HDTs. Not least of these was that, due to the emerging nature of the discussion surrounding HDTs, there is a particular need for further study of their implementation and design, as well as how they interact with behaviour change mechanisms. As such, while this paper brings together current understanding it also serves as a call to action for further research in this area.

Acknowledgements

This work has received funding from the Horizon 2020 research and innovation programme of the European Union under grant agreement no. 871767 of the project ReHyb: Rehabilitation based on hybrid neuroprosthesis.

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