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Human Digital Twin Modeling for Cardiovascular System

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Abstract.
Purpose: The cardiovascular system is a vital system responsible for the distribution of oxygen and nutrients throughout the body. The complexity of interactions between the heart and blood vessels often presents challenges in monitoring and analyzing health conditions. The research proposes the development of a Human Digital Twin (HDT) for the cardiovascular system through application of two different modelling approaches geometric modeling and physic-based modeling. Through this model physical conditions can be represented and real time data integrated to offer insights into the dynamics of the cardiovascular system.
Methods: This model development is based on two major components: a geometric modeling and a physic-based modeling. The geometric model is done in 3D to show the structure of the heart in detail, while the physical-based model is tabulated with different measurable physical parameters in the cardiovascular system, such as blood pressure and flow rate. This information is integrated into the Five Dimension Digital Twin model, including physical, virtual, data, connection, and service dimensions for the accurate simulation of cardiovascular conditions.
Result: Results confirm that the Five-Dimensional Digital Twin (DT) could give further development to how the dynamics of the cardiovascular system behave, possibly in real-time updates on conditions and a supply of data that is far more detailed in view of analyzing risk and further representation of specific cardiovascular disorders while providing personalized medical support.
Novelty: The Five-Dimensional Human Digital Twin Model (HDTM) developed in this research introduces novel innovations in the monitoring and simulation of the cardiovascular system through the application of geometric and physic-based modeling techniques. This approach offers a higher level of detail, compared to previous models, and added value for the advancement of health technology by integrating real time data into the simulations. This model serves not only as an advanced analytical tool but also as a reference for further research on DT technology in the medical field.

Keywords: Digital twin, Modeling, Geometric modeling, Physic-based modeling, Circulatory system
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INTRODUCTION

The cardiovascular system is one of the vital systems of the human body, which contributes majorly to the process of blood circulation and transportation of oxygen and nutrients to the tissues of the body [1]. It includes the heart, the blood vessels (arteries, veins and capillaries) and the blood which is circulated through these vessels to facilitate the distribution of carbon dioxide and metabolic products from the body to the outside environment [2]. In addition to this, the cardiovascular system is also involved in the process of thermoregulation through the mechanisms of vasodilation and vasoconstriction in order to keep the temperature of the body within the normal range [3]. There are two pathways by which the heart, the central organ of this system, pumps blood; these are the pulmonary circulation, which is the path taken by blood to the lungs to be oxygenated, and the systemic circulation, which is the path through which oxygenated blood is distributed to the body tissues [4].

This is crucial for the body to sustain homeostasis and general body health. With such a possibility, the potential for implementing the concept of the DT in the area of the cardiovascular system is greatly enhanced. The DT enables the creation of a precise digital replica of an individual's cardiovascular system, with information on arteries, veins, and capillaries. Through sensor technology and analytical techniques, this replica can reveal detailed information on the dynamics of blood circulation and the physiological responses of the body to different conditions. The concept of DT is today being extensively used for the

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cardiovascular system to enable more sophisticated medical analysis and treatment [5]. By having the capability to monitor and analyze in real-time, DT can help in the detection of cardiovascular problems at an early stage, tailor-made treatment, and enhance patient care outcomes. The use of this technology is likely to herald major transformation in the way we diagnose and treat heart ailments. The concept of DT technology evolved from the earlier two concepts: Digital Model and Digital Shadow [6].

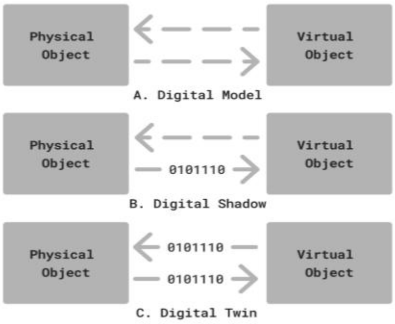

Figure 1. Development of DT technology: (A) Digital model – A virtual representation of a physical object without direct feedback. (B) Digital shadow – Data flows unidirectionally from the physical object to the virtual object for automatic updates. (C) Digital twin – Bidirectional interaction between the physical and virtual objects with real-time data exchange, allowing for more precise control and simulation.

Figure 1 illustrates the evolution of DT technology, which can be represented by three consecutive stages: Digital Model, Digital Shadow, and Digital Twin. The digital model means the virtual copy of the original physical entity (A), where no direct feedback happens such a type enables the structural and behavioral examination of the system. The second level is Digital Shadow (B), where data flows unidirectionally from the physical object to the virtual object for automatic updates, thus enabling condition monitoring continuously. The last stage is the Digital Twin (C), where there is a bidirectional interaction between the physical and virtual objects with real-time data exchange for more precise control and simulation. Such a process has important implications for modeling the heart and blood vessels for purposes related to cardiovascular conditions, for the representation of cardiovascular medical conditions, and in improvement in data-driven clinical decision support.

A **digital model** is the DT of its physical counterpart, aimed at achieving an advanced conceptual understanding of the structure and behavior of the systems through simulation and analysis. According to Grieves, the concept of the digital model was first adopted in the industrial sector for optimization purposes both in design and production. Since then, the concept has taken a new dimension and has been applied in various fields including the medical field [7]. **The digital shadow** is the virtual representation developed from passive data that different sensors or monitoring devices record in real time. According to Tao, the digital shadow is a key constituent of the DT concept, where data collected from wearable devices projects the physical condition of the patient continuously in digital form [8].

The digital twin is further development compared to the digital model and digital shadow. In a DT, the virtual representation of a real object is updated continuously by means of data received from sensors or monitoring devices [5]. It grants continuity in simulation, prediction, and optimization enabled [7]. The use of DT of the cardiovascular system in health applications always provides simulations related to the organ and blood flow, representing the real state of the present. This therefore presents better data to the doctors and researchers for the making of more effective decisions based on the evolution of a patient's condition [9]. The DT consists of three main elements: Physical Object, Virtual Object, and Connection. The three elements of the DT are illustrated in Figure 1 section c.

The fifth point is referring to the level of intelligence or service that is developed on top of the DT, which enables it to perform analysis, make decisions and simulate the behaviour of physical objects [10]. The extension of technologies such as AI and ML in the dimensions enhance the predictive and optimization capabilities within the model [11], thus giving more detailed information on individual health conditions in a medical context [12]. The five dimensional DT is illustrated by Figure 2 and it shows how these five dimensions are integrated into one ecosystem.

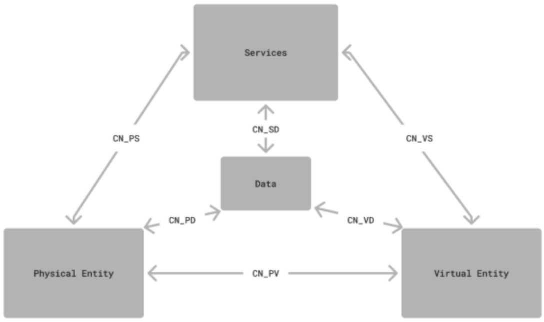

Figure 2. Five-Dimensional DT

Based on the five dimensions, the 5D DT provides a holistic approach to the management and monitoring of dynamic systems, including the cardiovascular system [6]. This allows simulation of medical interventions and review of outcomes based on continuously updated dynamic data [13], thus enabling doctors to better appreciate how patients are likely to respond to a treatment plan over the long term and predict the likelihood of complications [14]. Therefore, application of the 5D DT has a better outcome in personalized care and has the potential for more accurate medical decisions [15].

DT technology has been utilized in various fields, one of which is healthcare. The interaction between physical entities and virtual entities in DT allows for monitoring, diagnosing, and predicting health in the elderly [16]. With various features created using DT technology in healthcare, DT can provide a new paradigm in health personalization for patients [17]. DT can also replicate the real conditions of photovoltaic systems, enabling error detection and analysis, as well as improving operational efficiency and maintenance [18]. A new approach to predicting the lifespan of aircraft can also be implemented using DT technology. This approach can enhance safety and prevent aircraft from technical errors [19]. The utilization of DT technology has also significantly expanded, particularly in the manufacturing sector. The connection between physical entities and virtual entities allows for real-time control and monitoring, which is a key advantage of DT. With various services and available data, DT can provide support for making smarter manufacturing decisions [20]. Cyber-physical systems are also used to support dynamic systems in DT. With dynamic systems, workshops can become integrated and intelligent [21].

Modeling plays a crucial role in the development of DT, as it provides an accurate representation of complex physical assets, enabling real-time data synchronization between physical and digital entities [22]. Through modeling, users can conduct "what-if" scenario analyses to evaluate various possibilities without disrupting physical operations, as well as optimize design processes, quality control, and predictive maintenance. With a deep understanding of modeling techniques and twinning methods, the implementation of DT can be effectively carried out across various industries, from manufacturing to urban planning, thereby enhancing efficiency and reducing costs. Modeling is created to represent physical entities. Good modeling can precisely represent physical entities. The modeling proposed by Thelen is described in five forms: Geometric Modeling, Physics-based Modeling, Data-driven Modeling, Physics-Informed Machine Learning, and System Modeling. In the development of DT, geometric modeling and physics-based modeling serve as fundamental foundations, as both provide accurate representations of physical objects and system behaviors.

Geometric modeling focuses on visual and structural aspects, allowing for a clear understanding of shape and dimensions, while physics-based modeling uses physical principles to simulate interactions and dynamics between components, providing more accurate predictions of system performance. On the other hand, approaches such as data-driven models and physics-informed machine learning (ML), while effective in analysis and prediction, often fall short in terms of interpretability and deep understanding of physical mechanisms. Meanwhile, system modeling offers a holistic view of system interactions but may not always be as accurate in representing physical aspects and behaviors. Thus, geometric and physics-based modeling remain fundamental foundations in the development of effective and accurate DT.

Geometric modeling is one of the fundamental approaches in the development of DT, focusing on the visual and structural representation of physical objects. In this context, geometric modeling not only includes the creation of three-dimensional models of objects but also involves techniques to depict complex spatial relationships and dimensions. This approach is crucial as it provides a strong foundation for visualization, enabling users to accurately understand and analyze the shape and size of objects. In addition, geometric modeling plays a role in the integration of data from various sources, allowing DT to more effectively represent the real conditions of physical systems. By utilizing geometric modeling techniques, users can conduct in-depth simulations and analyses, which are crucial for data-driven decision-making. Therefore, a deep understanding of geometric modeling is key to the development of effective and efficient DT, as well as in enhancing the performance and reliability of the modeled systems.

Physics-based modeling is a crucial approach in the development of DT, leveraging physical principles to simulate the behavior of physical systems. This approach involves the use of mathematical models that describe the interactions and dynamics between components within the system, allowing for a deeper analysis of how the system operates under various conditions. By utilizing physics-based modeling, DT can provide more accurate predictions of system performance, which is essential in the context of predictive maintenance and data-driven decision-making. Furthermore, physics-based modeling also plays a role in the integration of data from various sources, allowing DT to more effectively represent the real conditions of physical systems. This approach not only enhances the accuracy of simulations but also enables users to conduct "what-if" scenario analyses that can assist in planning and risk management. Therefore, a deep understanding of physics-based modeling is key to the development of effective and efficient DT, as well as in improving the performance and reliability of the modeled systems.

The author is inspired by the challenges faced in the healthcare field, particularly in the development of DT technology that can enhance the understanding and management of cardiovascular conditions. Various existing studies demonstrate the significant potential of this technology in providing deeper insights into advancements in science and clinical practice. In this context, the researcher develops geometric modeling and physics-based modeling approaches to create accurate and dynamic representations of the cardiovascular system, which not only enable the simulation of physiological behavior but also support predictive analyses that can improve patient diagnosis and care. Thus, the development of these models is expected to make a meaningful contribution to efforts aimed at enhancing the quality of healthcare services and clinical outcomes.

This research aims to design geometric modeling and physics-based modeling to support the development of HDT in the cardiovascular system. The DT being developed not only considers physical parameters but also other variables that may depend on an individual's health condition. Thus, this model is expected to provide a more accurate representation of the patient's response to a medical treatment based on continuously updated data. This will assist in designing more personalized and effective care, thereby improving the quality of healthcare services.

Additionally, this research will also explain the methodology used to achieve these objectives. The geometric modeling approach will enable the visualization and analysis of the anatomical structure of the cardiovascular system, while physics-based modeling will facilitate the simulation of physiological dynamics occurring within the human body. The combination of these two approaches is **expected** to create a comprehensive DT model that can adapt to changes in the patient's health condition in real-time. Therefore, this research is anticipated to make a significant contribution to the field of personalized medicine and data-driven health management.

METHODS

The object of this research is the Digital Twin model of the human cardiovascular system, which includes two major parts: a geometric modeling and a physic-based modeling. The goal of the DT Model is to develop an accurate virtual model of the cardiovascular system that allows simulation, analysis, and real-time monitoring of blood circulation dynamics.

The research will be developed based on the 5D DT Model proposed by Tao, which is made up of five dimensions: physical object, virtual object, data, connection, and service. This approach is taken in order to develop an even more complete virtual representation where, in turn, each dimension contributes to the capability of the DT in depicting and analyzing the physical state and simulating conditions of the cardiovascular system in real time. In this DT modeling, the main focus will be on the aspect of modeling the physical entity into a virtual entity, referring to the concept proposed by Thelen. However, in this paper, two main aspects will be discussed: the geometric model and the physical-based model. The geometric model could be used to represent the shape and structure of the cardiovascular system, while in the physical-based model, the behavior and physical characteristics of blood circulation and cardiac dynamics are tried to be defined.

Geometric modeling

The geometric model represents graphically the parts of the cardiovascular system: the heart, vessels, arteries, veins, capillaries, and the flow of blood. It is done in 3D with the dimensions in size, shape, and the position each element has within the system. It would thereby allow geometric modeling-again, aided by 3D modeling software-but not just stop at visualization; this serves as a basis for analysis that proceeds beyond interaction among its constituent parts Precise geometric modeling in health and disruption is cardinal in understanding the manner of functioning of the cardiovascular system.

For the geometric model's enhancement, anatomy images repository resources are used to provide detailed and comprehensive references for the structures involved. These images are a most important resource when checking that the model gives a true representation of the real-world cardiovascular system's anatomy. The geometric model is also enriched with data from each patient individually to customize the model for specific anatomical variations and conditions. The conceptual model serves as the basis for the geometric model's development which both depicts physical objects and maintains patient-related information. This enables personalization as well as analysis and insights into cardiovascular health. Hence, geometric model has the ability to tackle the complexity of the cardiovascular system and its operation in the normal and diseased states.

Physic-based modeling

Meanwhile, the physic-based modeling focuses on representing the dynamic behavior of the cardiovascular system. This model integrates physiological data, such as blood pressure, blood flow, and heart activity, to simulate the real conditions of the cardiovascular system. This data is obtained from sensors and wearable devices that monitor health conditions in real-time, allowing the model to provide up-to-date information on the performance of the cardiovascular system. Thus, the physic-based modeling plays a vital role in supporting medical decision-making and more effective treatment. The two models are complementary: the geometric model and the physic-based modeling to provide a comprehensive DT of the cardiovascular system. This is where these models can couple with the behavioral data for more detailed analysis and better forecasting of the patient's health state. The potential of this research is the capability to create a digital model that can mimic different treatment plans as well as the monitoring function to support the improvement of cardiovascular health.

However, the proposed prediction model is a conceptual model at the first modeling process level. We have not yet considered performance accuracy in various conditions. Therefore, the object of this research will give an overview of new ideas in the health sector that apply digital modelling technology to bring in improvements and better care to the cardiovascular system. A digital model is a virtual representation of a real object in order to gain understanding of the structure and behavior of a system through simulation and analysis. Some physical objects have their twin in the digital world, which gives deep insights into the system's behavior and structure by simulating and analyzing the data.

This paper presents the output of HDTM as a conceptual model and then progresses to the design of a 3D model of the human heart and its blood vessels. The output of the 3D model is enhanced by the output from physic-based modeling that contains design data about the physical characteristics of the heart and the vascular system. Therefore, although this conceptual model has not yet been informed by performance accuracy, it still provides an important starting point for further development in more complex and accurate cardiovascular system modeling.

RESULTS AND DISCUSSIONS

It proposes the HDTM on cardiovascular systems to digitally represent the human circulatory system, including all vital organs comprising the heart, blood vessels such as arteries, veins, and capillaries, and blood. This model will allow simulation and visualization of various physiological processes, enabling a deeper understanding of cardiovascular dynamics. The implications of the HDT for cardiovascular health are significant, as it can facilitate personalized medicine by providing tailored insights into individual patient conditions and responses to treatments. Furthermore, this model can be integrated into various devices and settings, such as personal assistants, bedside clinicians, support diagnosis systems, and smart prescriptions, thereby enhancing the quality of care and improving patient outcomes through real-time monitoring and data-driven decision-making.

The proposed Five-Dimensional approach further includes real-time monitoring and simulation dimensions in which, at all times, information from the physical entity of a heart and vessels is being continuously gathered through sensors, artificially intelligently processed, and reflected in its digital entity. With such a broad DT in place, observations in five dimensions of a cardiovascular system would become possible: the physical entity, virtual entity, data, service, and connectivity. This model, when applied, will help in better management of patient data and provide advanced predictive healthcare services. The model used in Figure 3 is as follows.

The process of geometric modeling in the cardiovascular system begins with the collection of geometric data from the heart, blood vessels and blood flow with medical imaging techniques such as MRI or CT scans. This data is then processed and presented in 3D modeling software like Blender using Polygonal Modeling and Mesh Modeling to depict the physical structure of objects. After the basic model is created additional details such as the thickness of the heart walls and the branching of blood vessels are incorporated into the model. Simulations are then performed on this model to validate its accuracy and functionality for further analysis of the performance and condition of the cardiovascular system.

In the 3D model of the heart and blood vessels in Blender, the precision measurements are made using the Metric unit system whereby 1 unit is equal to 1 meter. *MeasureIt* and the *Ruler/Protractor* Tool in Blender are used to measure the dimensions of objects such as the length of blood vessels or the thickness of heart walls with high accuracy. The Snap Tool assists in aligning objects and the Grid is a visual reference. Using these tools, the 3D model can be adjusted to match medical data or real world scale and thus the model can be accurate and of good quality.

To create a physic-based model of the cardiovascular system, first gather wearable sensors data of the heart and blood vessels physical parameters. The wearable sensors including heart rate monitors, blood pressure monitoring devices, and blood flow sensors are meant to collect information on different aspects of the physiological process in real-time. Equipped with highly advanced technology for precise and lasting measurements, the data gathered includes the heart rate variability, the systolic and diastolic pressure, and the blood flow within the vessels. The gathered data is vital for developing an exact and comprehensible model of an individual's physical state as well as for further analysis of cardiovascular health.

After collecting the physical parameter data the next operation becomes the integration of this information into the digital cockpit system which is a subsystem of HDT System. The digital cockpit acts as a visual interface through which users obtain the monitoring and analysis of cardiovascular conditions in real time. The digital cockpit features include real time graphs, trend analysis and interactive data visualization that help users understand changes in the cardiovascular parameters over a period of time.

For instance, to visualize heart activity, a dynamic animation system will be used. This system enables users to view how the heart works in real-time, including the modifications that happen during activity or rest. With the help of dynamic animations, users will have a better understanding of how different stressors, including stress, physical activity, and sleep patterns, influence the functioning of the heart and blood vessels. This offers greater understanding of their cardiovascular health and allows users to implement necessary interventions to enhance heart health.

The digital cockpit, through the integration of data from wearable sensors and interactive visualizations, enables this physic-based modeling to offer both a static picture of the cardiovascular system and the ability to perform additional analysis to support better health management decisions. As a result, this physic-based modeling proves to be a vital component in creating an expanded and effective HDT that offers opportunities to improve healthcare quality and clinical results for individual patients.

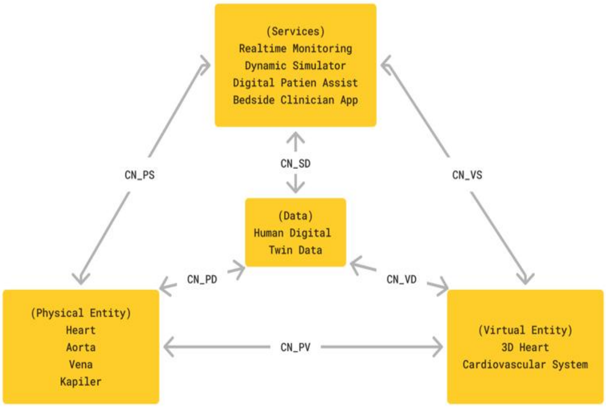

Figure 3. Five Dimensions Models of HDTM

Figure 3 illustrates the interactions among the main components in the 5D DT modeling of the cardiovascular system: Physical Entity, Virtual Entity, Data, Services, and Connectivity. The Physical Entity in this model includes physical organs such as the heart, aorta, veins, and capillaries, which are the focal points for monitoring. The Virtual Entity is a three-dimensional digital representation of the cardiovascular system that enables accurate simulation and analysis of various conditions.

The HDTM is comprised of five dimensions: physical objects, virtual objects, data, services, and connections. As for the physical parameters that can be used to create this model, there are several wearable devices and medical tools that provide the data needed to build this model. For instance, smartwatches are capable of tracking cardiovascular parameters like heart rate and blood pressure while fitness trackers are able to monitor physical activity and calories expended. Also, medical patches can give details on particular biomarkers and pacemakers can track heartbeats in real-time. This data is very important in the construction of a digital model of an individual's health status. The data from these devices is then communicated through different combinations of wireless technologies including Bluetooth and Wi-Fi, and also through wired connections like Ethernet. This system also uses cloud services for processing, storage, and networking to enable real time data access and collaboration among devices. As a result of this model, existing resources are used to develop several artificial intelligence (AI) modules that can analyze and representation health conditions, giving a more detailed view of an individual's health and thus enhancing the quality of care delivered.

In the context of developing DT for cardiovascular systems, three important relationships must be considered: CN_PS (Physical to Services), CN_PD (Physical to Data), and CN_SD (Services to Data). The CN_PS relationship illustrates how data obtained from physical entities, such as the heart, aorta, veins, and capillaries, is utilized by services to perform real-time monitoring and simulation. The information collected from these organs is critical in supporting operational services, such as health monitoring and dynamic simulation, which enable rapid responses to changes in patient conditions.

Subsequently, the CN_PD relationship elucidates how data generated by physical entities is employed to produce relevant and useful information within the health context. This data encompasses physiological parameters that can be analyzed to provide insights into an individual's cardiovascular condition. Finally, the CN_SD relationship (Services to Data) demonstrates the interaction between services and data, wherein the operational services can generate new, valuable data for further analysis. By integrating these three relationships, the DT system can offer a more comprehensive and accurate representation of the cardiovascular system, thereby supporting improved decision-making in healthcare.

Next, two important modeling processes for the HDT for the Circulatory System will be presented. The first is Geometric Modeling, which represents the heart and cardiac function in the form of 3D objects. The second is Physical-based Modeling, used to represent the physical parameters related to heart function. Some of this parameter data will be acquired through wearable devices, such as blood pressure, heart rhythm (ECG), pulse, and others. The modeling of physical entities in this study follows the approach proposed by Thelen in DT modeling theory, emphasizing the importance of synchronization between physical and virtual entities through real-time data. Thelen explains that DT modeling must be continuously updated by data from physical entities to support monitoring and representation of system conditions. This approach is highly relevant in the context of the cardiovascular system, where dynamic modeling of the heart and blood vessels allows for more accurate simulations and quicker responses to changes in patient conditions.

Geometric model

Geometric modeling within the frame of this study involves detailed models of the heart and vessels, with specified flow characteristics of blood through the modeled circulation system. Through this, the process is executed in 3D modeling, as well as the use of medical data such as CT scans, which deliver accurate models of the geometric structure of the heart. Good modeling not only enhances the accuracy of physical representations but also opens up opportunities for the development of more and higher-quality services. With more accurate and comprehensive models, healthcare providers can conduct more effective simulations, enabling them to design more precise and personalized interventions. This, in turn, can improve clinical outcomes and provide a better care experience for patients.

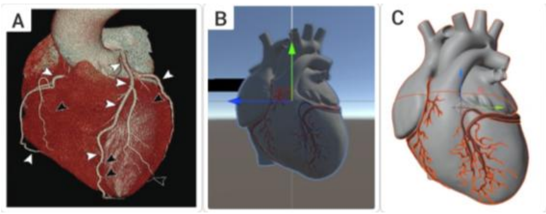

Figure 4. Heart Modeling Process in HDT: (A) Image from the Heart CT Scan showing blood vessels in detail. (B) Development of the 3D Heart model based on data from the CT Scan results. (C) Virtual representation of the heart in the HDT [58].

Figure 4 illustrates an example of the geometric modeling of the heart, which is the result of geometric modeling of the heart and blood vessels, produced from CT scan data and the 3D rendering process. This figure shows how the structure of the heart and blood vessels is presented digitally. The heart modeling process is depicted in Figure 4 during the development of the HDT in three main stages. In (A), the outcome of a heart CT scan is presented, which gives a good view of the heart and its blood vessels including the arteries and veins that are in charge of blood circulation. This is because the data from this CT scan is to be used in developing a more complex model. In (B), the 3D heart model is created based on the data derived from the CT scan. This 3D model is not only a replica of the physical heart but also contains information about blood flow and the heart's functional segments. In (C), the virtual heart in the HDT is shown, which combines geometric and physiological information to give a realistic simulation. This representation allows researchers and healthcare providers to make detailed studies and simulate treatment plans that can be useful in understanding and handling patients' cardiovascular problems in a better way.
Table 1 below lists selected physical parameters concerning the human cardiovascular system, rest values ranging from: heart dimensions and weight, blood pressure, to blood flow velocity in major vessels. The normal value for each of the listed parameter is given in the relevant unit. The above information is important for modeling the basis of the HDT of the cardiovascular system, providing comprehensive and precise data about the physiological status of the human cardiovascular system.

As Table 1 depicts, the main parameters of the cardiovascular system are the physical parameters. Various cardiovascular health aspects can be modeled by specific models which are built from individual parameters or sets of parameters. For example, heart dimensions together with blood pressure can be used to develop a model that models the heart's functioning during varying physiological states. Other parameters could also be joined with blood flow velocity to measure blood circulation efficiency and locate any potential problems. These parameters enable researchers and clinicians to create fit models that improve our knowledge of cardiovascular dynamics which results in better diagnostic and therapeutic approaches.

Table 1. Physic-Based Model of the Cardiovascular System

No	Level	Physical Paramter	Unit	Range
1	Heart	Heart Weight	gram	(m) male: 280-340 (f) female: 230-280
2		Heart Length	cm	12-13

3	Heart Width	cm	8-9
4	Heart Thickness	cm	+/-6
5	Heart Volume	ml	700-800
6	Left Ventricular Wall Thickness	mm	8-12
7	Right Ventricular Wall Thickness	mm	3-5
8	Resting Heart Rate	bpm	60-100
9	Light Activity Heart Rate	bpm	100-120
10	Intense Exercise Heart Rate	bpm	160-180
11	Blood Pressure	mmHg	120/80
12	Cardiac Output	liters/min	4.7-5.7
13	Stroke Volume	ml/beat	70
14	Stroke Aorta Diameter	cm	2.5-3
15	Aorta Length	cm	30-35
16	Artery Diameter	mm	4-6
17	Artery Wall Thickness	mm	2-3
18	Total Length of Arteries	km	100000
19	Vein Diameter	mm	5-7
20	Vein Wall Thickness	mm	1-2
21	Capillary Diameter	µm	5-10
22	Total Length of Capillaries	km	40000
23	Total Blood Volume	liters	4-6
24	Number of Red Blood Cells	milions cells/ µL	m: 4.7-6.1 f: 4.2-5.4
25	Red Blood Cell Diameter	µm	6-8
26	Number of White Blood Cells	cells/ µL	4500-11000
27	Number of Platelets	cells/ µL	150000-450000
28	Hemoglobin Content	g/dL	m: 13.8-17.2 f: 12.1-15.1
29	Blood Pressure in Major Arteries	mmHg	120/80
30	Blood Pressure in Capillaries	mmHg	20-30
31	Blood Pressure in Veins	mmHg	5-10
32	Blood Flow Velocity in Aorta	cm/sec	30-40
33	Blood Flow Velocity in Capillaries	cm/sec	0.03

Table 1 shows some physical parameters of the main organs in the human cardiovascular system: the heart, blood vessels (arteries, veins, capillaries), and the blood itself. The units of measurement for each parameter are presented, together with the value ranges, based on references to various scientific studies. These parameters are crucial for accurately modeling the cardiovascular system, as they provide essential data for understanding the physiological characteristics and functional dynamics of the heart and vascular network. However, it is important to note that this modeling must be validated and verified by clinicians and medical professionals to ensure its accuracy and applicability in real-world clinical settings. Such validation is essential to confirm that the model accurately reflects the complexities of human physiology and can be reliably used for diagnostic and therapeutic purposes.

CONCLUSION

The object of this research is the DT model of the human cardiovascular system, which includes two major components: geometric modeling and physics-based modeling. The main purpose of the DT model is to design and implement a precise virtual model of the cardiovascular system that can be used to simulate, analyze and monitor blood circulation in real time. Using the five-dimensional DT model of this research is intended to contribute to the understanding of cardiovascular functions and clinical decision making by providing detailed insights into the physiological responses of the patient. Therefore, it can be concluded that the integration of geometric and physics-based modeling in the Digital Twin framework provides important benefits for the research and management of cardiovascular diseases. This approach not only enables a more detailed analysis of blood flow and vascular responses, but also facilitates the development of patient-specific treatments. Consequently, the outcomes of this research may help to enhance the monitoring and treatment of cardiovascular diseases and, therefore, improve the patient's quality of life and the efficiency of healthcare management.

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