virtual worlds

Article

Applications of Digital Twins in the Healthcare Industry: Case Review of an IoT-Enabled Remote Technology in Dentistry

Yaser Maddahi [1,2,*] and **Siqi Chen** [3,4]

[1] Digital Twins Advisory Board, Next Generation Manufacturing Canada, Hamilton, ON L8P 0A1, Canada
[2] Department of Research and Development, Tactile Robotics, Winnipeg, MB R3T 6A8, Canada
[3] Faculty of Health Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
[4] School of Academic Studies, Communication Department, Technical Writing Program,
British Columbia Istituite of Technology, Burnaby, BC V5G 3H2, Canada
* Correspondence: ymaddahi@tactilerobotics.ca

Abstract: Industries are increasing their adoption of digital twins for their unprecedented ability to control physical entities and help manage complex systems by integrating multiple technologies. Recently, the dental industry has seen several technological advancements, but it is uncertain if dental institutions are making an effort to adopt digital twins in their education. In this work, we employ a mixed-method approach to investigate the added value of digital twins for remote learning in the dental industry. We examine the extent of digital twin adoption by dental institutions for remote education, shed light on the concepts and benefits it brings, and provide an application-based roadmap for more extended adoption. We report a review of digital twins in the healthcare industry, followed by identifying use cases and comparing them with use cases in other disciplines. We compare reported benefits, the extent of research, and the level of digital twin adoption by industries. We distill the digital twin characteristics that can add value to the dental industry from the examined digital twin applications in remote learning and other disciplines. Then, inspired by digital twin applications in different fields, we propose a roadmap for digital twins in remote education for dental institutes, consisting of examples of growing complexity. We conclude this paper by identifying the distinctive characteristics of dental digital twins for remote learning.

Keywords: digital twins; Internet of Things; dentistry; healthcare; robotics; haptics; augmented reality

check for updates

Citation: Maddahi, Y.; Chen, S. Applications of Digital Twins in the Healthcare Industry: Case Review of an IoT-Enabled Remote Technology in Dentistry. *Virtual Worlds* **2022**, *1*, 20–41. https://doi.org/10.3390/virtualworlds1010003

Academic Editor: Zhonghua Sun

Received: 22 July 2022
Accepted: 29 August 2022
Published: 2 September 2022

1. Introduction

Digital twins are the digital replicas of physical systems, either living or not. Digital twins' adoption is becoming more popular in many fields. Industries such as manufacturing [1], automotive [2], and energy [3] sectors are using digital twins for their ability to address multidisciplinary problems. Some include interweaving solutions of complex systems analysis, decision support, and technology integration. Digital twins have gained popularity with the help of Internet of Things technologies, as they allow for high spatial resolution monitoring of the physical twins, practically in real-time, by using microdevices and remote sensing to provide ongoing data transmission. Digital twins enable continuous information transmission through the system's lifecycle [4]. Digital twins can simulate system development and validation [5], and prevent system failures and undesired system states [6] due to their ability to successfully converge physical and virtual spaces [7].

The concept of digital twins as a way to merge virtual and physical assets in product lifecycle management was conceived first by M. Grieves [8]. Since the introduction of the concept by Grieves, many fields have adopted digital twins. As there is no widely accepted definition, each sector has its own definition of digital twins. Our study will use the Clark et al. definition: "A dynamic virtual representation of a physical object or system, usually across multiple stages of its lifecycle, that uses real-world data, simulation, or machine learning models combined with data analysis to enable understanding, learning, and reasoning. Digital twins can be used to answer what-if questions and should be able to present insights in an intuitive way" [9].

Multiple sectors, companies, and organizations have adopted digital twins, some of which include Siemens [10], General Electric, NASA, the United States Air Force [11], Oracle, ANSYS, SAP, and Altair [12]. In addition to the adoption of digital twins by these leading companies, the increased availability of commercial software tools with which to develop digital twins, such as Predix1 and Simcenter 3d2 [10], is compelling evidence of industries' increased interest in digital twin applications. Industries that adopt digital twin applications will see numerous benefits, such as reduced production times and cost, hidden complexity of integrating heterogeneous technologies, safer working environments, and more environmentally sustainable operations.

Questions arise regarding the benefits of digital twins for dental institutions' remote learning, the characteristics that differentiate them from currently remote education practices, and their design and implementation. Presently, artificial intelligence technology [13], big data [14], and the Internet of Things [15] are starting to converge in digital twin applications, and the benefits of this convergence are evident in disciplines that have adopted digital twin applications. Examples are visible in the agricultural production systems [16], which leverage information and communication technologies to design and implement the next generation of data, models, and decision support tools. Although there are numerous benefits of digital twin adoption which can be seen in the industries and disciplines currently using them, digital twin usage by dental institutions for remote learning is limited. The added value of digital twins in remote dental education needs more discussion.

This paper investigates the potential added value of digital twins' adoption by dental institutions for remote learning. To obtain this information, we first research how widely adopted digital twins are by the dental industry and the dental institutions, then investigate their reported benefits. Next, we will examine similarities between digital twin adoption in dentistry and other fields to identify opportunities of potential added value for dentistry. Our research questions are listed below.

- To what extent have digital twins been applied in dentistry?
- What is a potential application-based roadmap for digital twins' adoption in remote dental education?

We utilized a mixed-method approach to answer our questions. As initial investigative research suggested, digital twin usage in dentistry for remote learning is limited. Thus, a literature review alone would not be adequate due to the limited number of reported cases in the literature. Our approach consisted of a literature review of existing digital twins in dentistry, and a survey of case studies in other disciplines, to compare digital twin adoption levels in dentistry and explore potential future uses. We reviewed digital twin use cases in dentistry, and use cases in other disciplines, to determine how each case implements digital twins. Our aim was not to identify specific digital twin applications. Instead, we focused on generalizing them into abstract, representative use cases. With the chosen use cases, we investigated the levels of maturity, service types, and benefits offered. Our methodology is reported below; the results and challenges are presented in the following (Section 4). We also discuss our results related to the present state of digital twins' adoption in dentistry and other industries (Section 5) and the added value of digital twins, present a portable teaching–learning platform for remote education called DenTeach (Section 6) that uses digital twins technology, and present potential areas for future research (Section 7). The final section (Section 8) concludes our work with our proposed roadmap for digital twins' adoption in remote dental education.

The need for remote education has increased since COVID-19 was declared a pandemic. To reduce transmissions, social distancing and preventative measures saw global implementation. Workplaces were mandated to limit the number of employees in the office and to have employees work remotely. The same policies also applied to schools and universities. These implementations resulted in the shutdown of in-person classes, and educational institutes scrambled to adhere to the new government policies and still provide education for students. In the initial months of the shutdown, it was evident that the education system did not fully prepare for a remote teaching and learning system. García-Morale et al. noted the transition to virtual classes will have significant implications for the entire learning process. To transition from in-person to remote learning, educational institutes need to modify methods for assessing learning outcomes and reassessing the skills and competencies required of students [17]. In the case of dental education institutes, it was evident that not all classroom material would be immediately transferable to remote teaching, as many of the courses require students to get hands-on. This change was challenging for instructors and students who were required to self-isolate at home without access to dental equipment [18]. Surgical procedures and equipment handling are necessary components that allow students to develop the hands-on experience and skills required for patient safety and comfort [19]. Dental institutes need a solution for students to continue learning and practicing hands-on skills if in-class lectures and laboratories are not feasible.

We note that during the start of our research, the pandemic restrictions were still fully implemented. While in the final stages of publishing this paper, the pandemic restrictions have lessened, and in-class lectures have returned. Institutions continue to use remote learning as part of their curriculum, since remote education has many benefits, such as increased class size, lower costs, and increased accessibility. Institutions should have the option of continuing a remote educational curriculum. For these potential benefits, we continued our research on digital twin adoption in the field of dentistry for remote learning. We hope this paper can inspire interest and further research on digital twin adoption in dentistry, since there is limited research in this area. With the increased visibility of the benefits of digital twins, there will be more interest in developing and improving dental digital twins for remote learning. Our paper is the first study to present a roadmap for digital twins' adoption in remote dental education. The proposed roadmap can also be modified to apply to other areas of dentistry. We also present a solution to remote dental education in the case of the COVID-19 pandemic, and although the pandemic has mostly ended, COVID-19 will not be the last pandemic. We are now more adept at pandemic life, and our paper will provide a solution for remote dental education in the face of a new pandemic.

2. Methodology

To answer the second research question—"What is a potential application-based roadmap for digital twins' adoption in remote dental education?"—we first searched for peer-reviewed review papers on digital twin applications. Then we reviewed the use cases, the reported benefits they offered, the industries, and the levels of adoption. We list the results of the digital twin application in each case and its benefits. Next, we proposed potential application areas in dentistry and identified potential benefits based on the use cases in other disciplines. Below we summarize our different research stages.

Research Stages

The research was separated into three sections: (i) literature search; (ii) paper selection; (iii) content analysis.

In the beginning, we started with a literature search to find information on our research topic. We used online journal databases and Google Scholar to search for peer-reviewed articles that included the terms "digital twins", "digital twins remote education", "digital twins application", "digital twins health care", "dental digital twins" and "dental digital twins remote education". We reviewed all papers that included these terms and selected ones that defined the concept of digital twins, and discussed the use and application of digital twins in areas of health care, remote education, dental education, dentistry, urban planning, and agriculture. We chose a diverse range of industries to compare findings. Finally, after reviewing the selected papers, we gathered the findings, and using the findings we present a roadmap for digital twin application in remote education. Below we summarize the process of each research stage.

(i) Literature Search
  - Using Google Scholar to search for the terms: “digital twins”, “digital twins remote education”, “digital twins application”, “digital twins health care”, “dental digital twins” and “dental digital twins remote education”.

(ii) Papers Selection
  - Selecting papers that defined the concept and reviewing papers that included these terms.
  - Selecting papers that discuss the use and application of digital twins in these areas: health care, remote education, dental education, dentistry, and other industries, such as urban planning and agriculture, for comparison.

(iii) Content Analysis
  - Reviewing the selected papers and reporting the findings, i.e., benefits, level of adoption, and challenges.
  - Using the findings to present a roadmap of digital twins’ applications in remote education.

Figure 1 is a visualization of the steps to answer our second research question on a potential roadmap for digital twins’ adoption in remote dental education.

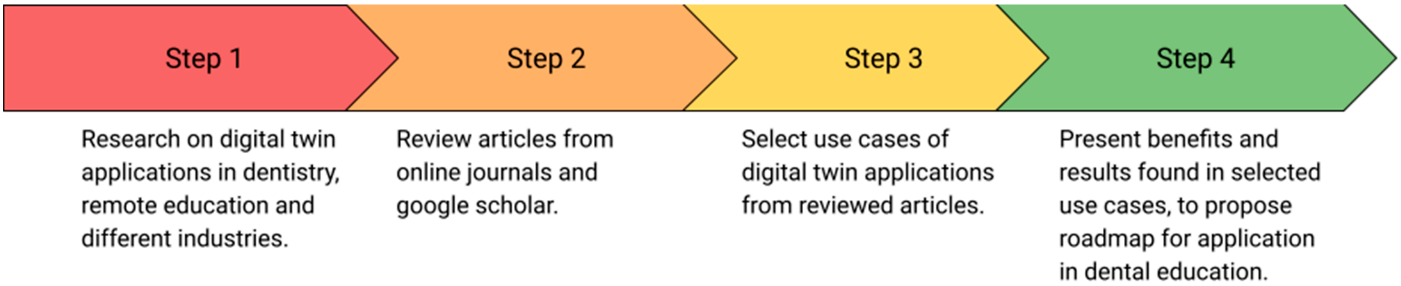


Figure 1. The steps to proposing a roadmap.

Roadmap for Digital Twins Adoption in Dental Education

We propose the roadmap below for the application of digital twins in dental education.

1. Target area to increase the awareness of digital twins. i.e., remote education.
2. Demonstrate benefits of digital twin application in remote dental education.
3. Increase interest and further research into digital twin applications.
4. Research begins for digital twin application in dentistry.
5. Develop digital twins for dental education and begin implementation of usage.

These steps are presented again in the Conclusions section.

3. Digital Twins: History

Digital twins are used mainly in advanced manufacturing and product lifecycle management [20]. Fuller et al. noted in their research that the number of papers on manufacturing is vastly higher than research on digital twins for smart cities and healthcare, highlighting gaps in these research areas [21].

The manufacturing industries use digital twins to improve uptime, worker safety, and high-efficiency activities [22]. The product lifecycle uses digital twins for product design, production line design, and production process optimization. Many businesses use digital twins to increase product performance because they allow companies to control their production processes, detect failures, and thus produce more efficient products [22].

Although digital twins’ usage is mainly in manufacturing, we expect to see more digital twins for healthcare and smart cities. In the future, we can expect to see digital twins being used with 3D printing to create body parts to treat soldiers on the battlefield [22].

The United States' military also has plans to develop virtual copies of their soldiers [22]. The demand for digital twins in many industries, such as healthcare, has increased since the COVID-19 pandemic.

What is the future of digital twins, and what challenges will arise? This paper will discuss how digital twins can be a solution to remote learning in dentistry. We will call attention to a specific platform called DenTeach that uses digital twin technology and how it can facilitate remote learning. We will also review the different applications of digital twin technology in health and non-health fields.

4. Digital Twins: Concept

First, we will provide findings from our literature review.

4.1. What Is a Digital Twin?

The concept of digital twins existed as early as 2002, but then had several different names, such as the mirror spaces model and the information mirroring model [23]. The term digital twin first came from John Vickers of NASA [23]. There are many different definitions found in the literature for digital twins. Most reports state that a digital twin consists of three main components: the physical product, the virtual product, and the data connection between the physical and virtual entity [24]. Boulous and Zhang separated digital twins into two types, composite and reference, also called proto-twins [25].

The development of digital twins technology has continued since its introduction to the terminology in 2010. In 2019 Carlos Miskinis, a digital twin research expert, predicted that up to 60% of global companies would use digital twins in 2020 [26]. Digital twin technology allows for monitoring product performance and increases productivity and effectiveness. A valuable feature of digital twins is the two-way information exchange between the physical and virtual twins [25]. This two-way information exchange allows for the complex digital representations of the physical twin, allowing for in-depth testing and better decision making without physically interacting with the physical object. Digital twins are becoming increasingly valuable and necessary for companies and organizations in all fields. The applications of digital twins in different industries are discussed in the sections below.

There are numerous articles on digital twins and their applications, but few about digital twins in education/training, and even less about their use in dentistry. That is to say, digital twin technology is relatively new in dentistry. There are many different uses of digital twins in health. Most digital twins in the health field are for health management, disease detection, monitoring, and testing drug effectiveness [25,27,28]. The trend for digital twins in the health field is toward personalized medicine. Data storage has already begun to allow for digital twins of all patients in the future. Developing a digital twin of the entire human body may not be possible anytime soon, as the human body is full of complex systems. If a digital twin developed for the most basic human system, i.e., cell receptors or some subcellular organelle, is possible, it will be significant for modern medicine. Agriculture is another field where digital twin technology is relatively new. One potential challenge for digital twins in agriculture is if too much focus is on the virtual twin, it may lead to neglect of the real-world systems [29].

4.2. Digital Twins: Technical Terms

We have listed the technical terms often used to describe digital twins in Table 1.

Table 1. Definitions of different terminology used within digital twin research.

Terms	Definitions	Examples
dynamic virtual representation	A virtual counterpart to a physical object, that mirrors and changes based on data transmitted through sensors.	IMU sensors attached to the handpiece measure movement and generate a 3D model which is superimposed on the video.
physical object	The physical counterpart of a digital twin which transmits data through sensors to the virtual model.	The handpiece held by the student has IMU sensors that track the student's hand movements.
system	A group of objects that work together for a common purpose.	The human body, or blood circulatory system.
lifecycle	The series of changes that a system goes through from beginning to end.	Beginning to end of a production line, from development to store shelves.
real-world data	The information collected by sensors on the physical object which is sent to the virtual object.	Hand movement, pressure, position.
simulation	A model that mimics a real-world process or system.	Flight simulation, for training astronauts or pilots.
human simulation	A model that mimics human systems.	A model of the human circulatory system generated by computers.
machine learning models	A program developed by computer systems to solve complex problems using algorithms.	Facial recognition within an image using databases of human faces.
remote learning	Learning is not restricted by location or time, i.e., students do not have to be physically present in a classroom.	Dental students can learn using the DenTeach platform anywhere in the world with an internet connection.

4.3. Needs for Digital Twins in Health Science Training

There is much research on digital twins in healthcare. In healthcare, the physical component of the digital twin model can be a patient [30]. Digital twins in healthcare can replace self-tracking and lead to faster disease detection, thereby allowing for treatment during the early stages of disease progression. Medicine testing drug effectiveness can be performed using the digital twins of patients and studying the effects of different drugs on virtual twins. Wei [20] discusses the main challenges of developing a human digital twin due to the complexity of the systems in the human body and different security and social problems with storing personal biological data.

Although much literature exists on digital twins in health fields such as personalized medicine and patient monitoring, not much exists for digital twins in health science training. Students need training on using digital twins, such as how to read values and different ways to interact with digital twins. It may be possible, in the future, for healthcare professionals to interact with the virtual aspect of the digital twins rather than the physical patient. If so, there would be a need for training on the different uses of digital twins in patient monitoring.

Although not much literature exists on digital twins in health science training, we may look at the results of digital twins' usage for training in other fields, such as engineering or laboratory courses, and the effectiveness in student learning.

Educators adapted their teaching methods to meet student's needs during the pandemic [19]. Bhute et al. reviewed how educators were adapting their teaching methods to include: reducing course workload and substituting conventional teaching practices with distance learning and virtual remote laboratories. Specifically, they discussed using digital twins as a tool for the transformative process of replacing in-person teaching with virtual laboratories.

Toivonen et al. listed the benefits of using digital twins in training, with one being larger groups of students [31]. With the ability to work remotely, the learning environment is not restricted to one classroom, allowing for larger class sizes. Another benefit of syncing the system operational data to the virtual model is that students can practice solving problems in realistic cases. The technology of the environment and the key learning contents of exercises will be in continuous feedback loops. Overall, digital twins allow for more versatile training.

Deniz et al. [32] reported that digital twins add flexibility to fulfill laboratory work requirements because expanding the number and capabilities of machines is relatively easy. Deniz et al. noted feedback from the Lucerne University students on using digital twins in learning as positive experiences. Many students reported digital twins were identical or better than in traditional laboratory settings. One benefit the students experience with digital twins is convenience, as they can access online laboratories any time, independent of place, and can repeat the experiments/exercises. Deniz et al. found the students were able to obtain conceptual knowledge effectively. Digital twins allow institutions to maintain the educational quality of laboratory experiments online while cutting costs.

Students for an online University course that Johra et al. [33] conducted also reported positive experiences and strong engagement while learning. Although the digital twins used in the online engineering course proved effective in learning, Johra et al. suggested that digital twins should not replace real-world laboratories but complement traditional experiments. They also reported that having students use digital twins as a learning tool increased their interest, perception, and understanding of different systems.

Harichandran et al. studied the use of digital twins for construction safety training. Their results show that training with digital twins and virtual reality (VR) could reduce accidents and loss of working hours, and improve worker productivity and overall performance [34]. In the article by Harichandran et al., they found that the information from digital twins can significantly improve VR training in many aspects.

4.4. Challenges

There are many benefits of digital twins, but also social-ethical issues that can hinder the widespread use of digital twins involving personal data [35]. There can be great social-ethical value with digital twins' usage in healthcare: prevention and treatment of disease, cost reduction, patient autonomy, patient freedom, and equal treatment. On the other hand, there are social-ethical risks: privacy and property of data, disruption of existing societal structures, inequality, and injustice. These social-ethical issues relating to patient privacy exist with personalized medicine. Thus, it is unclear how digital twins will affect the state of these issues and if they will improve or increase these issues. Policies are needed to avoid social and ethical issues and protect the individual rights of those using digital twins. These policies should ensure data privacy and protect personal biological information [25,31]. Digital twins need to be accessible for all and not a privilege to some, as it can lead to what Kamel Boulos and Zhang [25] called a "digital divide".

Another challenge is the type of data used. The data needed for a digital twin must be high quality, constant, and from an uninterrupted data stream. Low quality, inconsistent, and incomplete data can result in poor performance [21].

Companies using digital twin technology that store vast amounts of sensitive system data may face privacy and security issues. There must be updates in security and privacy regulations to protect against security breaches [21].

One ethical concern with depending on digital twins as a reliable source of information about a patient's health is that it can undermine the patient's authority and autonomy in the doctor–patient relationship. The digital twin data may be considered a more impartial view of the patient's health [36].

The commonly faced challenges seen with industry adoption of digital twins are listed below.

- ***Data Quality***: High-quality data are needed for the virtual twin to be statistically indistinguishable from its physical twin.
- ***Privacy***: Data security is needed to protect information from hackers.

- ***Ethical Concerns:*** Digital twins can worsen racial bias, leading to inequalities in healthcare [36,37], which can occur if a group has misrepresented data.
- ***Trust/Fear in AI:*** Healthcare professionals may not trust digital twin modeling for fear of being replaced. However, digital twins should support healthcare professionals rather than replace them [37].

There is also concern about data over-collection [38]. Regulations must be set in place to restrict service providers from collecting data not relevant to the service the digital twin service aims to provide. Collecting more personal information results in a greater risk of hacking attacks. Security measures must be current and monitored to detect hacking and prevent cyberattacks. Digital twins need to be reliable, and users should not be able to tamper with the digital twins and affect the quality and accuracy of the data. That is to say, users that have their data collected must not be able to exploit the device to compromise its quality and accuracy of the device. Information collection should be streamless, without data corruption, allowing service providers to make sound judgments based on digital twin data. Digital twins also face the challenge of digital obsolescence if the developers cease to provide service maintenance after system updates. There is a need for accurate user awareness of what they consent to when agreeing to share information on digital twins' usage. An increase in cyberattacks is another potential threat, as digital twins can store highly sensitive information and attract the attention of hackers. Algorithms can yield unexpected discriminatory results. Algorithms that create models from digital twins' information can overlook socio-environmental determinants, such as air pollution, water pollution, and lack of education, which are all factors that can contribute to health issues [38]. Overdiagnosis is another challenge when using digital twins in personalized health. One main goal of personalized healthcare is to provide early prevention. However, when preventative action occurs too early, it can lead to overdiagnosis and overtreatment [38].

Singh et al. reported that most of the challenges faced are due to the novelty of the technology, lack of consensus on its definition and value, lack of standards and regulations, lack of competent engineers and technicians, and lack of supporting software. Singh et al. also noted that although the current challenges are numerous, there is also a need to identify future issues that will arise with digital twin technology [39].

5. Digital Twins: Industry Adoption

5.1. Digital Twins in Healthcare

These days, numerous trackers and sensor devices are available to manage people's health and lifestyles. As a result, there is increased demand and expectation of higher quality healthcare. Digital twins can be a valuable tool to help with this demand. By creating dynamic models and human simulations, digital twins can improve patients' diagnostics, prognostics, and treatment plans [25]. There is so much more we can do with digital twins.

Voigt et al. suggested using digital twins to treat multiple sclerosis. They discussed how it can improve diagnosis, monitoring, and the well-being of patients; lower costs; and slow disease prevention. Voigt et al. noted that multiple sclerosis is a complex and multi-dimensional disease that involves enormous masses of data. Due to this reason, digital twins which solely function based on data would be particularly suitable to aid in disease treatment. Health care providers using digital twins would be able to process a substantial amount of data and provide effective personalized healthcare. Voigt et al. also noted that for the digital twins to be effective, the data collected and stored must be high quality, accurate, and consistent throughout the collection. The digital twin technology must use data that are regularly updated, analyzed, visualized, and correlated [37].

5.2. Smart Cities

There is increasing research on the use of digital twins for smart cities. Kamel Boulos and Zhang reported how digital twins using geographic information systems can create virtual cities that allow urban and public health planners to monitor floods and test out intervention scenarios, to predict how their population will be affected [25]. Government personnel can monitor and manage infrastructures such as traffic, transportation systems, power plants, utilities, water supply networks, waste, crime detection information systems, schools, libraries, hospitals, and other community services in real-time [40]. Data are collected from citizens, buildings, and other information sources [40]. Urban and public health planners can use the information from these smart cities to make informed decisions and implement appropriate actions or policies which can protect and improve the well-being of their communities. Digital twins of cities will allow for better disaster management and emergency planning by identifying risks [40,41]. They can advise pedestrians about highly polluted areas to avoid [40,41]. More national and regional governments are interested in creating digital twins for their cities [39,40]. There is currently a digital twin of Boston, Massachusetts, which is helping planners visualize future building plans, such as high-rises and skyscrapers. In addition, planners can assess their effects on the health and lifestyle of the surrounding community, i.e., how shadows affect the population's health throughout the seasons [25]. Other cities or countries can access data from these digital twins and improve their populations. Kshetri noted that digital twins of cities may not be helpful with social inequality and housing crises. Kshetri also noted that developing countries will not be able to benefit from digital twins, as there is a low degree of digitization in such places. Developed countries need to help developing countries with computing power and technical tools so developed countries can also benefit from digital twins [41].

5.3. Digital Earth

The next step after developing digital twins for cities is a digital twin for our planet. A virtual Earth, a highly ambitious project, is currently being worked on by the European Union (EU). They have named it Destination Earth, i.e., DestinE, and are planning to initiate it by 2027 [41]. The goal of DestinE is to monitor and simulate natural phenomena that occur in the atmosphere, oceans, ice, and on load, and the different effects of the human population on the planet. In addition to monitoring and simulating natural phenomena, the EU plans to test scenarios for developing environmental policies. The information provided by DestinE can allow policymakers to study climate change and develop strategies to combat the effects. Ultimately, DestinE will also be used to predict extreme weather conditions in advance to allow for disaster preparedness. Nativi et al. summed up the goal of DestinE as "to develop a dynamic, interactive, multi-dimensional, and data-intensive replica of the Earth (system), which would enable different user groups (public, scientific, private) to interact with vast amounts of natural and socio-economic information" [42]. A virtual Earth should receive and update data in real-time. As a live simulation model, the virtual twin should continuously learn and update based on changes in the physical twin. Specifically, DestinE will receive live information and Earth updates from Copernicus and other satellites [42].

5.4. Digital-Twins-Based Technologies in Dentistry

Although digital twin research in healthcare and other fields is vast, there are few digital twins in dentistry teaching or research. We will discuss in the below sections a platform called DenTeach that uses digital twins technology.

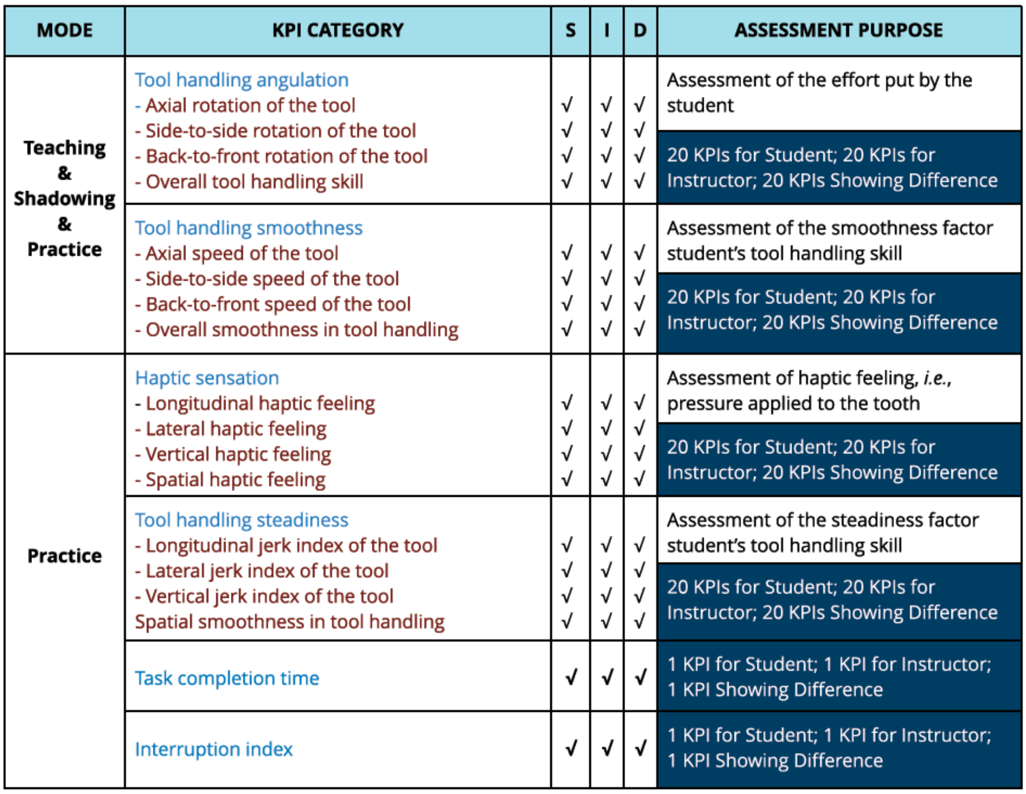
DenTeach is a portable teaching-learning platform for remote teaching and learning in dentistry [18,43,44]. DenTeach uses digital twin technology for learning and teaching purposes. In the below segments, we will discuss the digital twin technology and its application in remote learning.

6. DenTeach: A Viable Example of Implementation of Digital Twins in Dentistry

As illustrated in Figure 2, there are two types of DenTeach workstations available [43]: the instructor workstation (left) and the student workstation (right). The instructor workstation consists of a DT-Rightway dental articulator [43], a sensory system, four 360-degree view cameras, a microphone for live communication, and software that displays students' information and performance. The student workstation consists of a DT-Rightway dental articulator, a sensory system, two sets of RealFeel dental handpieces, and software that stores students' performance and provides KPIs. The workstation monitor displays a 3D model superimposed on the student RealFeel drill.

Figure 2. DenTeach comprises the DT-Instructor (instructor workstation) and DT-Student (student workstation) that communicate through a cloud-based communication channel.

A list of KPIs is shown in Figure 3. The KPIs are calculated to assess the tool handling angulation, the smoothness and steadiness of the student's hand motion, and the amount of the haptic sensation generated during the performance of each dental task.



MODE	KPI CATEGORY	S	I	D	ASSESSMENT PURPOSE
Teaching & Shadowing & Practice	Tool handling angulation - Axial rotation of the tool - Side-to-side rotation of the tool - Back-to-front rotation of the tool - Overall tool handling skill	 √ √ √ √	 √ √ √ √	 √ √ √ √	Assessment of the effort put by the student 20 KPIs for Student; 20 KPIs for Instructor; 20 KPIs Showing Difference
	Tool handling smoothness - Axial speed of the tool - Side-to-side speed of the tool - Back-to-front speed of the tool - Overall smoothness in tool handling	 √ √ √ √	 √ √ √ √	 √ √ √ √	Assessment of the smoothness factor student's tool handling skill 20 KPIs for Student; 20 KPIs for Instructor; 20 KPIs Showing Difference
Practice	Haptic sensation - Longitudinal haptic feeling - Lateral haptic feeling - Vertical haptic feeling - Spatial haptic feeling	 √ √ √ √	 √ √ √ √	 √ √ √ √	Assessment of haptic feeling, *i.e.*, pressure applied to the tooth 20 KPIs for Student; 20 KPIs for Instructor; 20 KPIs Showing Difference
	Tool handling steadiness - Longitudinal jerk index of the tool - Lateral jerk index of the tool - Vertical jerk index of the tool Spatial smoothness in tool handling	 √ √ √ √	 √ √ √ √	 √ √ √ √	Assessment of the steadiness factor student's tool handling skill 20 KPIs for Student; 20 KPIs for Instructor; 20 KPIs Showing Difference
	Task completion time	√	√	√	1 KPI for Student; 1 KPI for Instructor; 1 KPI Showing Difference
	Interruption index	√	√	√	1 KPI for Student; 1 KPI for Instructor; 1 KPI Showing Difference

Figure 3. A list of KPIs used in DenTtach library to assess each student's performance. S, I, and D

indicate the student's KPIs, the instructor's KPIs, and the difference between the student and the instructor's KPIs. $\surd$ represents a check mark showing that the KPI is calculated in student (S), instructor (I) or the difference of student and instructor (D) index.

Results from studies on virtual educational systems and dental simulators in remote educational settings are positive [18]. Students report using the virtual practice systems and dental simulators as positive experiences and had visible improvements in their practical skills. However, many of these simulators are not widely used due to costs and portability issues. We believe DenTeach could be a more suitable option for remote learning than other existing methods.

6.1. DenTeach Physical Setup

DenTeach complements the traditional instructor and student working area by integrating itself into the existing working setup (which consists of a tabletop, dental unit, and dental instruments).

6.1.1. Instructor Workstation

The instructor work area shown in Figure 1-left is the DenTeach platform integrated with a standard instructor work area and dental unit. This workstation consists of the DT-Performer, DT-Rightway Articulator, DT-RealFeel Sensors, and four mini cameras. The DT-Performer features a full classroom view, a selectable student profile, and a performance index. The sensors are wirelessly attached to the standard dental drills, which can measure and collect quantitative performance data. Each sensor is state-of-the-art technology that records and streams the instructor's hand motion data to the cloud (recorded data are then imported live to each student's workstation). DT-Performer interprets data in real-time and provides advanced statistical data analysis to rate the student's performance as a quantitative value. During each test, there is measurement of the orientation data and dynamic information. The information that is analyzed includes roll (axial), pitch (back-to-front), and yaw (side-to-side) angles, linear accelerations (3 DOFs), angular accelerations (3 DOFs), angular velocity (3 DOFs), jerk components (3 DOFs), and several KPIs.

In summary, the main components of the instructor workstation are listed below.

- **DT-Instructor**: the platform contains all components and 4 HD cameras to provide different views (see Figure 4) of the instructor station.
- **DT-Performer**: software that provides a classroom view, selectable student profiles, interprets data in real-time, and displays students' performances.
- **DT-Rightway Articulator**: a custom-designed system that supports upper and lower typodonts.
- **DT-RealFeel Sensors**: measure quantitative performance data.

6.1.2. Student Workstation

Figure 2-right shows the student's work area. This workstation consists of the DT-Student, a fully integrated system with two typodonts affixed to the DT-Rightway Articulator, a student's DT-RealFeel Handpiece to synchronize the instructor's movements while in teaching mode, and DT-Student software to allow recording and playing of lesson videos. Lesson videos are demonstrated with psychomotor performance metrics to measure effort, speed, accuracy, and learning curve. In addition, the system also has four selectable instructor videos. In each video, the student's drill model is superimposed over the instructor's drill to enable effective imitation. The custom-designed DT-RealFeel Handpiece has a handle grip with a built-in actuation system to generate a vibrotactile feeling, a set of sensory systems, and a data communication system. Excess force triggers the built-in vibrator to send an abrupt jolt to the hand. The workstation processing unit calculates several performance indices, and each index uses one or more operating characteristics detected by the sensory system within the DT-RealFeel Handpiece. The instructor's DT-Performer also uses its data to measure similar performance indices.

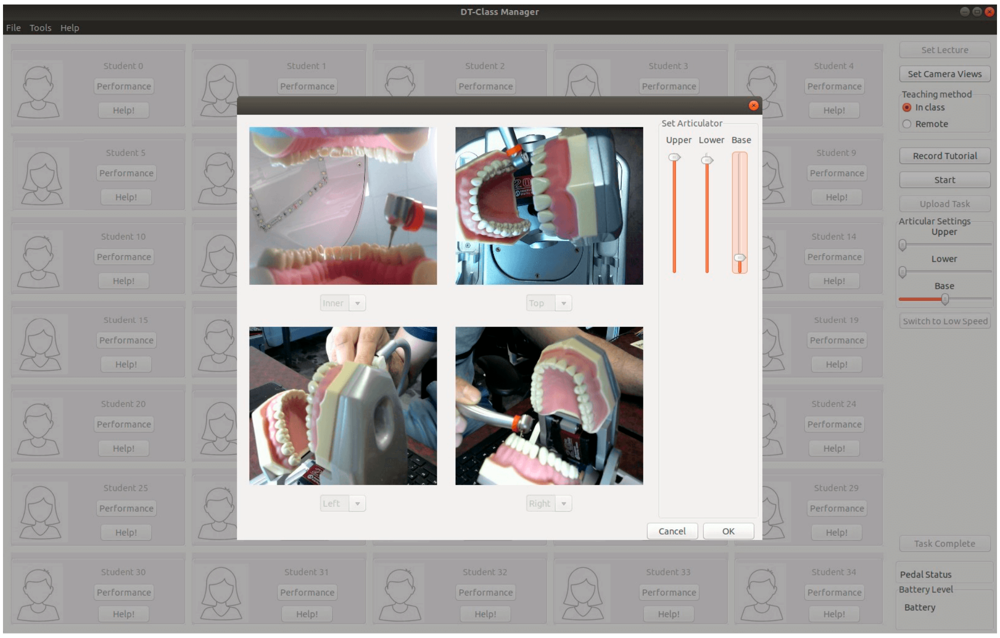


Figure 4. An instructor can set up the view of each camera through which students can watch the task remotely.

In summary, the main components of the student workstation are listed below.

- **DT-Student**: the central platform contains all elements of the student station.
- **DT-RealFeel Handpiece**: a drill with sensors in the handle, which can generate a vibrotactile feeling and act as an alarm to notify students.
- **DT-Student software**: allows for the viewing and recording of instructor videos and displays students' performance metrics, allowing students to view their learning progress.

An augmented reality feature superimposes on the instructor's video shown in Figure 5 (digital twins concept).

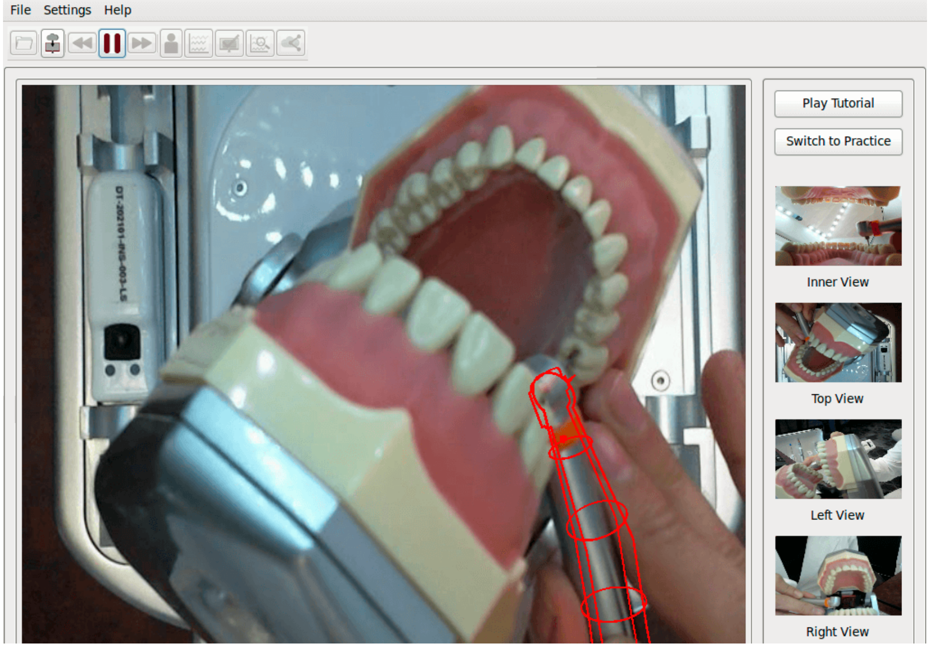


Figure 5. Students benefit from the superimposed 3D model of their handpiece in the video over the instructor's drill to understand how to hold the tool properly.

Four mini cameras on the instructor's workstation show the top view, two side views, and inside view of the DT-Rightway Articulator, and the instructor's hand position during teaching procedures. They can also record and simultaneously transmit onto the students' workstations. In addition, the instructor can select, record, and play over 30 psychomotor performance metrics using the DT-Performer software, so the instructor can objectively measure effort, speed, accuracy, and learning curve.

6.1.3. PrepScanner Unit

PrepScanner is an automated measurement system for providing the measurements of a tooth for use by a dental instructor or a dental student to assess dental performance (Figure 6). The PrepScanner is used at a student or instructor's workstation as a standalone platform or in combination with a DenTeach's DT-Student or DT-Instructor workstation [44]. PrepScanner has an application that shows measurements and dimensions and statistical and graphical information on the dental performance of the student during a dental procedure. The PrepScanner provides high-accuracy preparation measurement by giving students access to a high-quality preparation grader which employs robotics and laser technology. Access is available regardless of time or location. In addition, students can use this virtual tutor for self-assessment of dental preparations and receive quantitative feedback and a comprehensive report immediately on measurements of a dental preparation (Figure 7), with accuracy as high as 20 microns.

Figure 6. PrepScanner is an automated measuring device that provides fast, precise, and objective tooth preparation grading.

6.1.4. DenTeach: Digital Twin Technology

DenTeach uses the digital twin concept to teach students the correct hand position during teaching procedures. The platform includes the DenTeach Digital Twins API designed for DenTeach Library (see Figure 8), dashboards for both student and instructor workstations, data analysis/analytics implemented in DenTeach Library, and the simulation environment in the shadowing model of the student software.

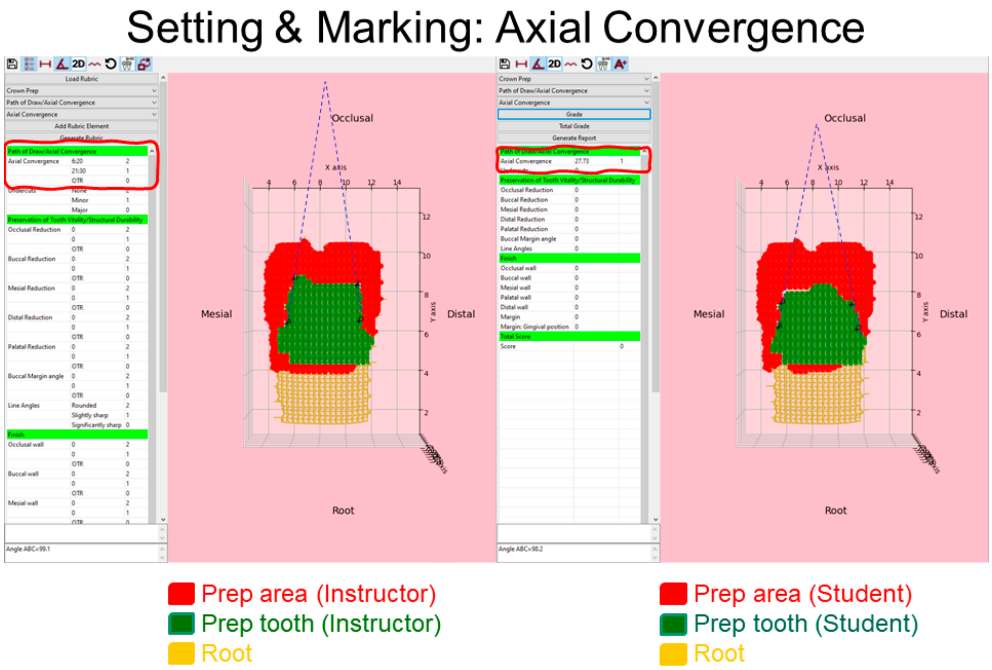
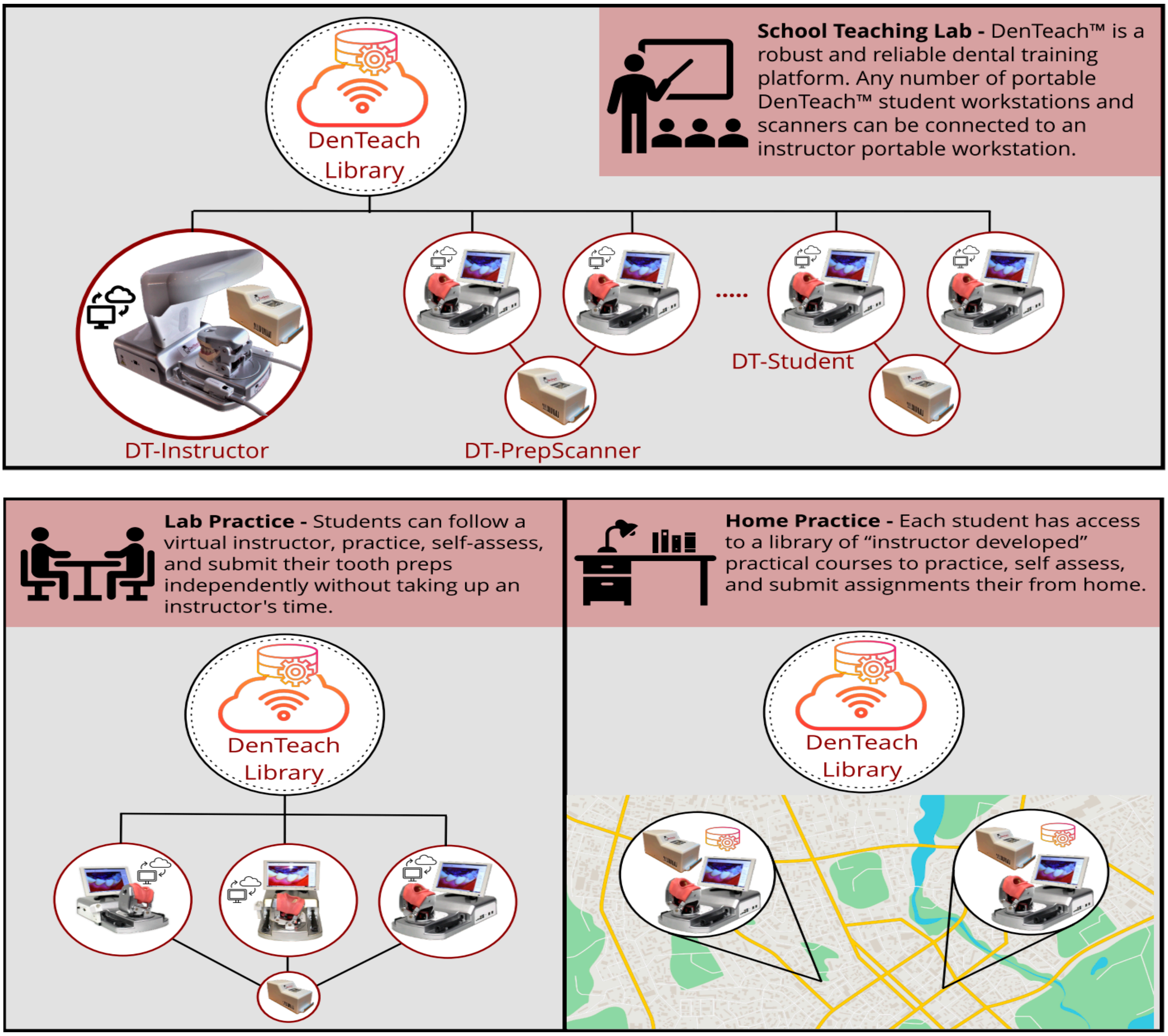


Figure 7. PrepScanner visualizes the marking environment for dental students and instructors. It also allows students to understand their performances and compare their work with their instructor.

Figure 8. DenTeach Library is the brain of the DenTeach platform that connects data and information among the student workstations, the instructor workstation, and the scanner.

Figure 5 shows the augmented reality concept of the digital twins used in DenTeach. IMU sensors on the handpiece record and transfer information from the student's hand movement and display it on the screen as a superimposed 3D model, i.e., augmented reality. The students can understand the concept of the course by combining both physical and virtual presentations of the tooth and dental instruments. The physical twin is the student's hand drill, and the virtual twin is the 3D-imposed hand drill model displayed in the instructor's video. The student's hand drill and the 3D-imposed model are connected by sensors, allowing for real-time data transmission and display. The student's hand drill's movement is viewable directly on the instructor's video as an augmented model. Using this digital twin concept, students can accurately position their hand drills during teaching procedures and will visibly see when their hand drill positions stray from the instructor's. Students can instantly know when they are doing anything incorrect or different from the instructor. In a real-class setting, teachers would be present to watch a student's hand position and point out errors, but with digital twin technology, DenTeach lets students watch for their own mistakes (see Figure 9). In addition, a virtual twin of each student stores the performance metrics, and their physical actions are measured as KPIs and updated in real-time onto the student's profile. DT-Performer software stores any changes or new data transmitted to the virtual twin. The instructor can review the student's profile (virtual twin) and analyze their progress regardless of physical proximity to the student (physical twin); i.e., the instructor can view all changes to the virtual twin remotely. In addition, all data updates are in real-time, so the students' information displayed is accurate to their current abilities.



School Teaching Lab - DenTeach™ is a robust and reliable dental training platform. Any number of portable DenTeach™ student workstations and scanners can be connected to an instructor portable workstation.

Lab Practice - Students can follow a virtual instructor, practice, self-assess, and submit their tooth preps independently without taking up an instructor's time.

Home Practice - Each student has access to a library of "instructor developed" practical courses to practice, self assess, and submit assignments their from home.

Figure 9. DenTeach usage in a live class with other students and the course instructor (with or without PrepScanner) or as a practice **unit** without the need for the instructor's presence.

6.2. Flexible Applications

There are two different combinations for using DenTeach:

- Live classroom application. Each student synchronizes with the instructor (Figure 6—top).
- Students practice solutions. Each student can work individually with the virtual instructor (the cloud or DenTeach Library stores the recorded class materials).

6.3. Case Studies

We reviewed the two existing articles on DenTeach: Cheng et al. first [45] and the one by Maddahi et al. second [18].

6.3.1. Proof of Concept

Cheng et al. conducted a case study on DenTeach to measure the KPIs and the system's ability to help the instructors teach and help the students learn more effectively compared to existing traditional techniques. In the case study, the instructor completed three dental tasks while the student followed along at the student workstation. The three tasks performed were Class I, II, and V composite preparations, which Cheng et al. described as involving different lesion sizes and caries, for active practicing on a plastic tooth characterized by rheostat engagement and drill operation [45]. The tasks were: Task 1: Class I composite preparation on tooth 46. Task 2: Class II composite preparation on tooth 45. Task 3: Class V composite preparation on tooth 46.

The student followed the instructor's motion reasonably well using DT-RealFee Handpiece. The student's motion deviations were within a range expected by the instructor and were within the acceptable interval set by the instructor. There were three recorded times with higher deviation than the interval set. For Task 2, there were two deviations, and for Task 3, there were four. Note that the student adjusted their hand positioning to be within the allowable range once the RealFeel Handpiece notified the student of excessive deviation. After completing Tasks 1, 2, and 3, the instructor and the student received the KPIs. Cheng et al. stated that the combination of KPIs, video views, and graphical reports in teaching and shadowing mode helps students understand the areas they need to improve [45]. In all KPIs reported, the student's standard deviation was higher than the instructor's, indicating the need for the student to improve in all areas.

In shadowing mode, the student used the RealFeel Handpiece to review the tasks taught by the instructor. In this mode, students can acquire more quantitative feedback to help them become confident and prepare for practice mode by providing hands-on practice with the actual dental handpiece. Shadowing mode saves material and time with minimal supervision [45]. Students are not restricted to in-person laboratories, as DenTeach can be used anywhere with an Internet connection to practice dental operations. In the reported study, the student performed five trials of Task 1 in shadowing mode. They performed assessments using the three Euler angles, the student's deviations from the instructor's, and the amount of pressure exerted on the tooth. KPIs reported from trial 1 to trial 5 show that the ranges of motion in trial 5—axial, side-to-side, and back-to-front rotations—decreased by 52.4%, 25.9%, and 74.9% compared to trial 1. Additionally, the standard deviations in both angulation and speed components were reduced from trial 1 to trial 5. The KPIs presented from the DenTeach sensors showed that the student's ability to handle the tool in a more limited workspace and a smoother manner improved from trial 1 to trial 5.

In practice mode, the student uses the real dental handpiece to practice the three tasks. For this mode, a wireless sensory system identical to the instructor's sensors is used to measure the signals and calculate the KPIs. The sensory system and camera record and communicate the audiovisual vibrotactile information to the database. The system then compares the recorded audiovisual vibrotactile data from the student with the instructor. At the end of each trial, the student can submit the results and the audiovisual signals to the instructor.

For this part of the study, the student had ten trials to complete. Cheng et al. reported that the student achieved improved scores in most of the KPIs, including the haptic jerk index, used to assess the steadiness of tool handling. The maximum alues of longitudinal, lateral, and vertical jerk indices decreased by 1.3%, 64.8%, and 25.8%, respectively. The results indicate that the student's hand steadiness improved from trial 1 to trial 10. After the ten trials, the student could complete the task 25.5% faster than in the first trial. In addition, the interruption index improved by 43.7%, indicating the student was more confident in handling the handpiece in the last trial than in the first trial.

6.3.2. Ethical Aspects in DenTeach

The second existing article on DenTeach relates to roboethics. Roboethics is necessary because it helps set up guidelines for dealing with moral dilemmas arising in robotics [18]. Maddahi et al. rated DenTeach on principles of data, common good, and safety in a case study and listed potential ethical considerations for DenTeach's implementation.

Privacy, Security, Longevity: To protect students' privacy, students should only have access to their performance information, whereas the instructor can see all student data [18]. Additionally, as the recorded information is in servers and cloud-based storage, it is necessary to have cybersecurity in place to protect from hackers. The integrity of the instructor's assessment is void if the stored data are tampered with; i.e., measures need to be in place to avoid compromised data.

In terms of longevity, DenTeach allows for remote software upgrades. In addition, Tactile Robotics provides a 4-year guarantee and 24/7 tech support for DenTeach [18]. For software updates, access to instructor's data, and contact tech support, users of DenTeach will need a stable Internet connection. Maddahi et al. recognize that while most of North America has access to the Internet, some areas may still not have a stable Internet connection. Dental schools should take into consideration the accessibility of Internet services when accepting international students situated abroad.

Benefits of DenTeach: DenTeach is for remote learning during a pandemic, but this is not its sole beneficial use. DenTeach allows for unbiased quantitative feedback to students, which is vital, as dental schools require program standardization and objective evaluation [18]. In addition to an impartial evaluation system, all students receive learning material the same way, as the content exists on a server.

Students can use DenTeach for self-study and self-analysis due to the available education modes (shadowing and practice mode) and the built-in software that tracks and displays the student's progress in the form of KPIs. Maddahi et al. noted that self-study and self-analysis are vital steps in mastering dental techniques.

As DenTeach is portable, dental schools can admit students from areas without dental schools, which benefits the students and their communities. Providing global teaching and learning is relevant, as it supports the principle of equitable access to technology. Maddahi et al. noted this as one of the ten ethical principles for developing artificial intelligence (AI).

Another quality of DenTeach that allows for inclusive learning is the ambidextrous setup. The setup allows for both left-hand and right-hand users [18]. Students can practice in a way that is natural and comfortable for them.

Safety: Although the setup includes a dental drill and is a few pounds in weight, physical harm or death from DenTeach is unlikely. Maddahi et al. believe that safety is not a significant concern for DenTeach, as it would require a person to have malicious intent or an accident to result in physical injury. As such, safety would not be a significant issue.

6.3.3. Pandemic Impact

Both Cheng et al. and Maddahi et al. reported on how DenTeach is valuable for education systems, and how can help students and teachers with remote training challenges. DenTeach is portable and affordable, making it a good way for dental institutes to continue their education during the pandemic. Much like the other digital twins for student learning listed in the previous sections, DenTeach can increase teaching efficiency by accelerating skill acquisition by students and removing limitations based on classroom size [18,45]. DenTeach provides extensive quantitative feedback (KPIs) and performance data, allowing students to learn and practice individually. Using the sensors, actuators, and augmented reality environment, students can learn the proper handling of dental tools [18]. DenTeach provides real-time video, audio, feel, and posture information while synchronizing the operations of the instructor and the student. Instructors can analyze the different needs of students from the KPIs generated from the software and evaluate their skill levels [45]. The case study by Cheng et al. [45] on DenTeach for remote education showed that a combination of KPIs, video recordings, and graphical reports in different learning modes effectively help the student evaluate their skill levels and help them to improve.

6.3.4. Traditional Learning vs. DenTeach

The existing review of how DenTeach compares to traditional teaching is positive. The results of the DenTeach case study demonstrated that the KPIs, video views, and graphical reports from teaching and shadowing modes help students understand which areas of their work need further improvement [45].

Table 2 is a summary of the main differences between traditional learning and DenTeach. The most obvious difference between traditional learning and DenTeach is the physical setting of the student's learning environment. As DenTeach can be used remotely, there is unrestricted classroom size, and lessons can be accessed regardless of time and distance from the instructor's location.

Table 2. Traditional learning vs. DenTeach.

	Traditional	Traditional + DenTeach™	Advantages of the DenTeach™ System
Physical Workstation	Traditional Student Workstation (Tabletop, Dental Unit, Video Monitor)	Traditional Student Workstation Portable DenTeach™ Unit	Enhanced Student Learning Industry 4.0 Technology Portable
Instructor Software	None	DT-Class Manager™ (Student Selection, Performance Manager)	Objective Performance Assessments
Student Software	None	DT-Student™ (Video Integration, Augmented Reality, DT-Performer™)	Integrated Video Augmented Reality RT Performance Assessment
Video Feeds	1 Camera View (Top View Only)	4 Integrated Cameras (Top, Inside, and Side Views)	360 View Using HD Cameras
Instructor Drill	Real Drill	Real Drill RealFeel™ Sensors Advanced Measurement Kit	Drill Vibrations and Forces Synchronized to the Student
Student Drill	Real Drill	RealFeel™Drill (Synchronized to Instructor in Teaching Mode)	Drill Vibrations and Forces Synchronized to the Instructor Experience Actual VAF
Student Practice	Typodont (Tabletop)	Typodont (Tabletop) DT-Rightway™ Articulator/Typodonts	Patients Posture, Real Environment Typodont Orientation Synchronized to the Instructor

6.3.5. Adoption and Implementation: Requirements

Hartmann and Van der Auweraer noted that digital twins should enforce requirements for successful employment in standard industrial practice [46]. Requirements:

- **Interactivity—**The value of digital twins depends on speed and accuracy. High accuracy can result in time-consuming processes. Increasing the speed while retaining accuracy is vital for extending the use of digital twins.

- **Reliability**—Users of digital twins should not have to be experts, except during their use in design and engineering. Any prediction by the digital twin must be accurate or display a percentage of error, so users of all skill levels can interpret the results. In addition, digital twins must be self-aware and notify users if they are outside their area of usage.
- **Usability**—Simulation tools presently are designed for experts, but expert resources are limited, so the use is limited by the availability of experts. Digital twins' development needs a usability perspective to allow users to include non-experts.
- **Security**—Business models based on the digital twin may require an exchange of digital twins between parties. Measures must be in place to prevent reverse engineering and protect privacy and intellectual property.
- **Deployability**—Digital twin usage is different depending on the users and their goals. Distribution should be simple to reduce barriers and efforts.
- **Synchronicity**—Digital twins connect the virtual and physical worlds. The virtual twin must adapt to synchronize with its physical twin, including adapting based on physical breakdowns, reconfiguration, and service replacements.

7. Future of Digital Twins

The widespread use of digital twins in the future is foreseeable. With the improvements in augmented reality (AR) technology and significant cost savings from using digital twins, it is not surprising that more and more companies are integrating digital twins into their daily usage.

In a recent report by the NGen's Digital Twins Advisory Board [47], 83% answered that lack of funding for digital twins was the main reason digital twins' adoption in Canada is not more widespread. More funding for digital twin research and development in Canadian organizations is needed to prevent Canada from trailing behind other countries studying digital twins.

With companies like Meta (previously Facebook) heavily invested in AR and the Metaverse, digital twins could be the next step to advancing virtual economies. Imagine a future where people can use wearable technologies such as smart glasses to interact with their real-life surroundings to see a digital overlay and relevant information viewable only through their glasses.

Allam and Jones predicted some ambitious uses of digital twins in the future: People might experience and explore virtual environments through digital twins of physical and biological worlds. People of all occupations might use digital twins to create virtual twins of their work subjects and objects to observe, monitor, and alter the physical objects remotely in real-time. People might operate large business enterprises remotely without being physically on-site through digital twins [40,42].

Saddik et al. explored the future of digital twins and listed some possible uses in preventative medicine, social interactions and dating, raising children, and sports [48].

For preventative medicine, they suggested that patients use digital twins to look at their virtual selves, monitor their health and illnesses, and visualize any other happenings inside their bodies. Patients can access and view their medical records, health information, eating behavior, sleep data, and workout data, thereby allowing them (or healthcare professionals) to visualize their health state at any time.

In social interactions and dating, digital twins can help match single people together more successfully. Digital twins can allow for more accurate dating profiles. They can let people simulate situations with potential partners. Digital twins can help reduce fake profiles and better predict the compatibility of two people.

Saddik et al. suggested using digital twins to help parents with raising children. Parents can interact with the digital twins of their children to relay messages and provide instructions indirectly. With the increasing use of technology among children, and as more households have both parents working concurrently, digital twins may be a viable solution to help parents remotely interact with and teach their children.

In sports, digital twins can store an athlete's data for each game they play to help them understand how to practice and perform better. The athlete can access the stored information after each game to assess their play style and determine where they need improvement. The data can be from wearable trackers on the athlete or even sensors built into the ball and equipment.

In dentistry, we believe more digital twin technology will be developed further. Hopefully, many more studies will demonstrate the unlimited potential of digital twins in dentistry and remote dental education. We also note that as digital twin technology is still emerging, the term "digital twins" may also keep changing and updating to include more tools. Much like how the earliest computers were used for calculations and now include much greater functions, we may eventually see digital twins become more complex in their functionalities.

We summarize our proposed roadmap in Figure 10 for digital twins' adoption in dental education based on the findings from our case review.

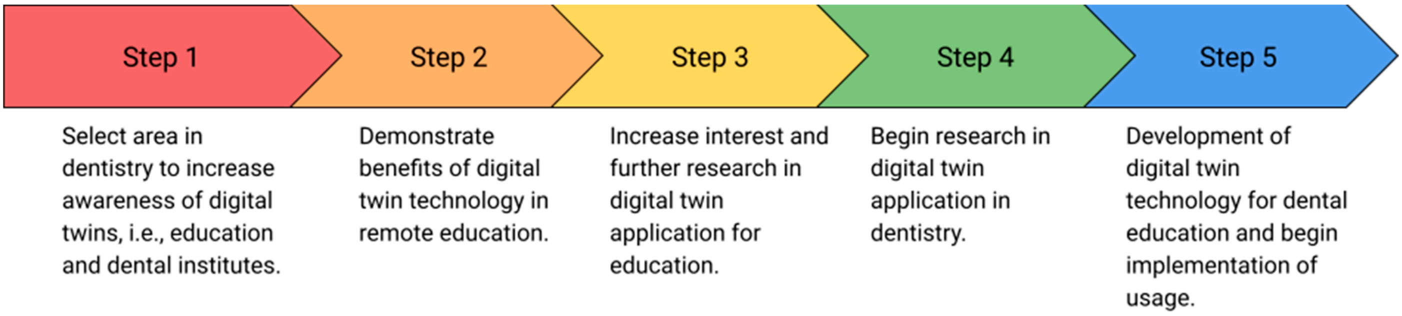


Figure 10. Roadmap for digital twin adoption in dental education.

Finally, for future research papers, we suggest a proposal for a reference to digital twin architecture in the dental field.

8. Conclusions

The use and research of digital twins have increased in many fields since their introduction. There is increasing use of digital twins and many privacy challenges. DenTeach, the teaching-learning platform that uses digital twins, could be the solution for remote learning in dental education. As institutions continue to improve remote education to remove the limitations of in-person lectures and laboratories, DenTeach is providing a new method for teaching students remotely. DenTeach uses a combination of KPIs, video feeds, and graphical reports in different education modes to allow students to improve their dental skills. DenTeach is an effective remote training tool due to its compact and portable size. DenTeach uses the digital twins concept to help students understand their lessons by combining both physical and virtual presentations of the tooth and dental instruments.

9. Patents

The DenTeach, DT-Rightway Dental Articulator, and DT-PrepScanner have been disclosed by Maddahi A., Bagheri S., Mardan M., Kalvandi M. and Maddahi Y.—inventors; Tactile Robotics Ltd., assignee. Vibrotactile method, apparatus, and system for training and practicing dental procedures. United States patent application US 17/271,470. 2021—Maddahi Y., Kalvandi M., Maddahi A. and Asadi A.A., inventors; Tactile Robotics Ltd., assignee. Automated dental articulator and method for training and practicing dental procedures. United States patent application US 17/115,166. 2021 and Maddahi Y., Kalvandi M., Maddahi A., and Dhannapuneni P., inventors; Tactile Robotics Ltd., Automated apparatus and method for quantifying dimensions of dental preparations. United States patent application US63/164,759. 2022.

Author Contributions: Conceptualization, Y.M.; methodology, Y.M. and S.C.; investigation, Y.M. and S.C.; resources, Y.M. data curation, Y.M. and S.C.; writing—original draft preparation, Y.M. and S.C.; writing—review and editing, Y.M. and S.C.; visualization, Y.M. and S.C.; supervision, Y.M.; project administration, Y.M.; funding acquisition, Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Tactile Robotics for providing technical input on the content of this manuscript.

Conflicts of Interest: Yaser Maddahi is with Tactile Robotics, and his name is on the patents related to the DenTeach technology. The rest of the authors declare no conflict of interest.

References

1. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine* **2018**, *51*, 1016–1022. [CrossRef]
2. Caputo, F.; Greco, A.; Fera, M.; Macchiaroli, R. Digital twins to enhance the integration of ergonomics in the workplace design. *Int. J. Ind. Ergon.* **2019**, *71*, 20–31. [CrossRef]
3. Sivalingam, K.; Sepulveda, M.; Spring, M.; Davies, P. A Review and Methodology Development for Remaining Useful Life Prediction of Offshore Fixed and Floating Wind turbine Power Converter with Digital Twin Technology Perspective. In Proceedings of the 2018 2nd International Conference on Green Energy and Applications (ICGEA), Singapore, 24–26 March 2018; pp. 197–204.
4. Haag, S.; Anderl, R. Digital twin–Proof of concept. *Manuf. Lett.* **2018**, *15*, 64–66. [CrossRef]
5. Boschert, S.; Rosen, R. Digital twin—the simulation aspect. In *Mechatronic Futures*; Springer: Cham, Switzerland, 2016; pp. 59–74.
6. Grieves, M.; Vickers, J. Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary Perspectives on Complex Systems*; Springer: Cham, Switzerland, 2017; pp. 85–113.
7. Tao, F.; Cheng, J.; Qi, Q.; Zhang, M.; Zhang, H.; Sui, F. Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 3563–3576. [CrossRef]
8. Grieves, M. Digital Twin: Manufacturing excellence through virtual factory replication. *White Pap.* **2014**, *1*, 1–7.
9. Clark, A.S.; Schultz, E.F.; Harris, M. What Are Digital Twins? Technical Report, IBM. 2019. Available online: https://developer.ibm.com/articles/what-are-digital-twins/ (accessed on 21 July 2022).
10. Negri, E.; Fumagalli, L.; Macchi, M. A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manuf.* **2017**, *11*, 939–948. [CrossRef]
11. Mukherjee, T.; DebRoy, T. A digital twin for rapid qualification of 3D printed metallic components. *Appl. Mater. Today* **2018**, *14*, 59–65. [CrossRef]
12. Qi, Q.; Tao, F.; Zuo, Y.; Zhao, D. Digital Twin Service towards Smart Manufacturing. *Procedia CIRP* **2018**, *72*, 237–242. [CrossRef]
13. Patrício, D.I.; Rieder, R. Computer vision and artificial intelligence in precision agriculture for grain crops: A systematic review. *Comput. Electron. Agric.* **2018**, *153*, 69–81. [CrossRef]
14. Wolfert, S.; Ge, L.; Verdouw, C.; Bogaardt, M.J. Big data in smart farming–a review. *Agric. Syst.* **2017**, *153*, 69–80. [CrossRef]
15. Elijah, O.; Rahman, T.A.; Orikumhi, I.; Leow, C.Y.; Hindia, M.N. An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges. *IEEE Internet Things J.* **2018**, *5*, 3758–3773. [CrossRef]
16. Janssen, S.J.C.; Porter, C.H.; Moore, A.D.; Athanasiadis, I.N.; Foster, I.; Jones, J.W.; Antle, J.M. Towards a new generation of agricultural system data, models and knowledge products: Information and communication technology. *Agric. Syst.* **2017**, *155*, 200–212. [CrossRef] [PubMed]
17. García-Morales, V.J.; Garrido-Moreno, A.; Martín-Rojas, R. The Transformation of Higher Education After the COVID Disruption: Emerging Challenges in an Online Learning Scenario. *Front. Psychol.* **2021**, *12*, 616059. [CrossRef]
18. Maddahi, Y.; Kalvandi, M.; Langman, S.; Capicotto, N.; Zareinia, K. RoboEthics in COVID-19: A Case Study in Dentistry. *Front. Robot. AI* **2021**, *8*, 612740. [CrossRef] [PubMed]
19. Bhute, V.J.; Inguva, P.; Shah, U.; Brechtelsbauer, C. Transforming traditional teaching laboratories for effective remote delivery—A review. *Educ. Chem. Eng.* **2021**, *35*, 96–104. [CrossRef]
20. Shengli, W. Is human digital twin possible? *Comput. Methods Programs Biomed. Update* **2021**, *1*, 100014. [CrossRef]
21. Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access* **2020**, *8*, 108952–108971. [CrossRef]

22. Erol, T.; Mendi, A.F.; Doğan, D. Digital Transformation Revolution with Digital Twin Technology. In Proceedings of the 2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Istanbul, Turkey, 22–24 October 2020; pp. 1–7.
23. Grieves, M.W. Virtually Intelligent Product Systems: Digital and Physical Twins. In *Complex Systems Engineering: Theory and Practice*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2019; pp. 175–200. [CrossRef]
24. Wagner, R.; Schleich, B.; Haefner, B.; Kuhnle, A.; Wartzack, S.; Lanza, G. Challenges and Potentials of Digital Twins and Industry 4.0 in Product Design and Production for High Performance Products. *Procedia CIRP* **2019**, *84*, 88–93. [CrossRef]
25. Boulos, M.K.; Zhang, P. Digital Twins: From Personalised Medicine to Precision Public Health. *J. Pers. Med.* **2021**, *11*, 745. [CrossRef]
26. Miskinis, C.M. The Mysterious History of Digital Twin Technology and Who Created It. Challenge Advisory. 2019. Available online: https://www.challenge.org/insights/digital-twin-history/ (accessed on 10 March 2022).
27. Semakova, A.A.; Zvartau, N. Data-Driven Identification of Hypertensive Patient Profiles for Patient Population Simulation. *Procedia Comput. Sci.* **2018**, *136*, 433–442. [CrossRef]
28. Troncoso, Á.; Ortega, J.A.; Seepold, R.; Madrid, N.M. Non-invasive devices for respiratory sound monitoring. *Procedia Comput. Sci.* **2021**, *192*, 3040–3048. [CrossRef] [PubMed]
29. Pylianidis, C.; Osinga, S.; Athanasiadis, I.N. Introducing digital twins to agriculture. *Comput. Electron. Agric.* **2021**, *184*, 105942. [CrossRef]
30. Jeske, S.J. Digital Twins in Healthcare. 2020. Available online: https://projekter.aau.dk/projekter/files/360456256/Jeske_MasterThesis.pdf (accessed on 17 December 2021).
31. Toivonen, V.; Lanz, M.; Nylund, H.; Nieminen, H. The FMS Training Center-a versatile learning environment for engineering education. *Procedia Manuf.* **2018**, *23*, 135–140. [CrossRef]
32. Deniz, S.; Müller, U.C.; Steiner, I.; Sergi, T. Online (Remote) Teaching for Laboratory Based Courses Using "digital Twins" of the Experiments. *J. Eng. Gas Turbines Power* **2021**, *144*, 051016. [CrossRef]
33. Johra, H.; Petrova, E.A.; Rohde, L.; Pomianowski, M.Z. Digital Twins of Building Physics Experimental Laboratory Setups for Effective E-learning. *J. Phys. Conf. Ser.* **2021**, *2069*, 012190. [CrossRef]
34. Harichandran, A.; Johansen, K.W.; Jacobsen, E.L.; Teizer, J. A Conceptual Framework for Construction Safety Training using Dynamic Virtual Reality Games and Digital Twins. In Proceedings of the 38th International Symposium on Automation and Robotics in Construction, Dubai, United Arab Emirates, 2–4 November 2021. [CrossRef]
35. Popa, E.O.; van Hilten, M.; Oosterkamp, E.; Bogaardt, M.-J. The use of digital twins in healthcare: Socio-ethical benefits and socio-ethical risks. *Life Sci. Soc. Policy* **2021**, *17*, 6. [CrossRef] [PubMed]
36. Mittelstadt, B. Near-term ethical challenges of digital twins. *J. Med. Ethic* **2021**, *47*, 405–406. [CrossRef]
37. Voigt, I.; Inojosa, H.; Dillenseger, A.; Haase, R.; Akgün, K.; Ziemssen, T. Digital Twins for Multiple Sclerosis. *Front. Immunol.* **2021**, *12*, 669811. [CrossRef]
38. Huang, P.-H.; Kim, K.-H.; Schermer, M. Ethical Issues of Digital Twins for Personalized Health Care Service: Preliminary Mapping Study. *J. Med. Internet Res.* **2022**, *24*, e33081. [CrossRef]
39. Singh, M.; Fuenmayor, E.; Hinchy, E.P.; Qiao, Y.; Murray, N.; Devine, D. Digital Twin: Origin to Future. *Appl. Syst. Innov.* **2021**, *4*, 36. [CrossRef]
40. Allam, Z.; Jones, D.S. Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies. *Land Use Policy* **2021**, *101*, 105201. [CrossRef]
41. Kshetri, N. The Economics of Digital Twins. *Computer* **2021**, *54*, 86–90. [CrossRef]
42. Nativi, S.; Mazzetti, P.; Craglia, M. Digital Ecosystems for Developing Digital Twins of the Earth: The Destination Earth Case. *Remote Sens.* **2021**, *13*, 2119. [CrossRef]
43. Maddahi, A.; Bagheri, S.; Mardan, M.; Kalvandi, M.; Maddahi, Y. Vibrotactile Method, Apparatus, and System for Training and Practicing Dental Procedures. U.S. Patent 17,271,470, 28 August 2019.
44. Maddahi, Y.; Kalvandi, M.; Maddahi, A.; Dhannapuneni, P. Automated Apparatus and Method for Quantifying Dimensions of Dental Preparations. U.S. Patent 63,164,759, 23 March 2021.
45. Cheng, L.; Kalvandi, M.; McKinstry, S.; Maddahi, A.; Chaudhary, A.; Maddahi, Y.; Tavakoli, M. Application of DenTeach in Remote Dentistry Teaching and Learning During the COVID-19 Pandemic: A Case Study. *Front. Robot. AI* **2021**, *7*, 611424. [CrossRef] [PubMed]
46. Hartmann, D.; Van der Auweraer, H. Digital twins. In *Progress in Industrial Mathematics: Success Stories*; Springer: Cham, Switzerland, 2021; pp. 3–17.
47. NGen's Digital Twins Advisory Board: Expert Opinions Survey. 2022. Available online: https://f.hubspotusercontent20.net/hubfs/5005023/Documents/TAP/NGen_Digital-Twin%20Report_0218.pdf?utm_medium=email&_hsmi=204855561&_hsenc=p2ANqtz-9Uxrjef7F0HEtrK5FLB6-sHRqPCsrN4T0pYegMramNAi0LFwoFNb1jZCscLM2XzXLA2iv8QDV4vRubraN6_3zmxFx3vaZjwPq3QZQ5CXa0n5jBARI&utm_content=204855561&utm_source=hs_email (accessed on 23 February 2022).
48. El Saddik, A.; Laamarti, F.; Alja'Afreh, M. The potential of digital twins. *IEEE Instrum. Meas. Mag.* **2021**, *24*, 36–41. [CrossRef]