Frontiers in Health Informatics
ISSN-Online: 2676-7104
2024; Vol 13: Issue 3
www.healthinformaticsjournal.com
Open Access

Revolutionizing Prosthodontics: The Power of Artificial Intelligence

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Cite this paper as: Sumit Aggarwal, Yashika Bali, Dimple Chawla (2024) Revolutionizing Prosthodontics: The Power of Artificial Intelligence. *Frontiers in Health Informatics,13* (3), 42-51.

Abstract
Artificial intelligence is gaining widespread attention globally due to its significant breakthrough in intelligence innovation. Its application spans across various fields. Particularly in the realm of Prosthodontics, AI serves as a vital tool, aiding in the design of prostheses and the creation of functional maxillofacial appliances. Moreover, it plays a crucial role in patient documentation, diagnosis, treatment planning, and patient management, thereby enabling dental healthcare professionals to work more efficiently and effectively. This review aims to illuminate the integration of AI in prosthodontics, showcasing the current advancements in AI and machine learning technology within dental prosthetics. It underscores the effectiveness of AI in diagnosing conditions and fabricating prostheses tailored to individual patients. Ultimately, it enables dental healthcare professionals to enhance efficiency and effectiveness in their work.

Keywords: artificial intelligence, dentistry, prostheses, maxillofacial appliances, diagnosis, innovation

INTRODUCTION

Throughout the ages, humanity has been shaped by the evolution of technology, and today, we stand on the brink of a new era marked by the emergence of Artificial Intelligence (AI). The primary component of AI involves a network of artificial neurons designed to replicate the learning process of the human brain, promising significant positive transformations in our contemporary society. Consequently, researchers and scientists are diligently and continuously striving to propel the field of Artificial Intelligence forward. In 1956, during a workshop at Dartmouth University, mathematician John McCarthy coined the term "artificial intelligence," earning him recognition as the pioneer of this field. Richard Bellman (1978) characterized artificial intelligence as "the automation of activities associated with human thinking abilities, which includes learning, decision making and problem solving".[1] The AI model's ability to make predictions is dependent on previously gathered digitalized data, which is constantly evolving. The AI model is made up of an artificial neural network that is based on both weak AI and strong AI. Machine learning, neural networks, and deep learning are subsets of artificial intelligence. Machine learning serves as the bridge between the realms of weak and strong AI. It forms the bedrock of AI, enabling weak systems to learn from data, while deep learning constructs towering structures of neural networks, representing the ascent towards stronger, more adaptable forms of artificial intelligence.[2] AI is transforming various industries and enhancing human capabilities across finance, transportation, manufacturing, agriculture, retail, education, and notably, dentistry in healthcare. Robotic automation and assistive technologies have been used to increase accuracy in dentistry. Robots may free up human resources for other critical activities, such as interacting with patients, require sophisticated cognitive ability. The merging of artificial intelligence and prosthodontics heralds a new era, where technology and artistic precision intertwine to create smiles that captivate with their wonder. Through the aid of robots, prosthodontics is undergoing a transformation, with tasks such as CAD/CAM fabrication, 3D printing of dental prostheses, precise implant surgeries, and rehabilitative support becoming more efficient and precise, ultimately leading to improved patient outcomes. AI-assisted 3D navigation implant systems are revolutionizing the field, enabling clinicians to meticulously plan, execute, and verify implant placements, thereby catalyzing significant global change.[3]

History and Evolution of Artificial Intelligence

Warren McCulloch and Walter Pitts proposed neural networks in 1943 as a method of imitating human brains. In 1949, book The Organisation of Behaviour: A Neuropsychological hypothesis, author Donald Hebb introduced the hypothesis that brain pathways are formed as a result of experiences, and that connections between neurons become stronger the more they are used. Hebbian learning remains an essential AI model. Alan Turing's 1950 publication "Computing Machinery and Intelligence" proposed what is now known as the Turing Test, a method for assessing whether a machine is intelligent. In 1959 Allen Newell, Herbert Simon, and J.C. Shaw created the General Problem Solver (GPS), a programme that simulates human problem-solving. There were two big winters: the first in the late 1970s, caused by AI's perceived limitations, and the second in the late 1980s and early 1990s, there was a high expense associated with establishing and maintaining expert digital information databases. In 1997 IBM's Deep Blue beats world chess champion Gary Kasparov. Apple integrates Siri, an assistant with voice in the year 2011 and amazon integrates alexa in the year 2014. In 2016, Google‘s DeepMind's AlphaGo defeats world champion Go player Lee Sedol. In 2022, OpenAI announced ChatGPT (Chat Generative Pre-trained Transformer), a text-generation model capable of producing human-like responses based on text input.[4,5]

Working of AI Model

A strong AI system, achieved via sophisticated software engineering and artificial hardware, emulates human intelligence by encompassing key elements such as reasoning, problem-solving, decision-making, planning, learning, and communication. This entails the machine's adeptness at performing human tasks and effectively replicating or imitating human behavior. Weak AI seeks to enhance the cognitive behavior and decision-making abilities of computer systems, aiming to embed these capabilities within them, rejecting unjustifiable simplification, and striving to emulate human intelligence, a goal envisioned and pursued by strong AI.[6]

Weak AI comprises of:

1. Machine learning

It is a discipline of computer science that develops algorithms based on data. It is one of the sections in AI that provides knowledge to computer systems through data and observations without having to programme them. Abdalla-Aslan et al. (2020) investigated machine learning computer vision algorithms. They utilized an automated algorithm for restoration detection and classification, along with a support vector machine algorithm employing error-correcting output codes for cross-validation. The results indicated that machine learning exhibited outstanding performance in detecting and categorizing dental restorations within panoramic images.[7]

It is classified into four learning areas (Table 1):

- Supervised Learning: The computer possesses a dataset for tracing that has been accurately labeled by a human expert.
- Unsupervised Learning: The computer operates without utilizing a tracing dataset but instead attempts to autonomously gather data without human intervention, segregating the data into clusters or groups.
- Semi-supervised Learning: Supervising every dataset is challenging, hence, combining a substantial volume of unlabeled data with a limited amount of labeled data can enhance the accuracy of machine learning.
- Reinforced Learning: As per Hal Varian, it represents the sequential experimentation of a computer, aiming to attain a goal through interactions with a dynamic external environment.[8]

Table 1: A comparison of supervised learning, semi-supervised learning and unsupervised learning.

Items	Supervised learning	Semi-supervised learning	Unsupervised learning
Input type	Labelled data	A mixture of labelled and unlabelled data	Unlabelled data
Accuracy	High	Mid	Low
Complexity of the algorithm	Low	Mid	High
Types of algorithm	Regression and classification	Regression, classification, clustering, and association	Clustering and association

2. Neural Networks
Artificial neurons strive to replicate the structure of the human or biological brain, enabling them to recognize patterns, structure data, and acquire knowledge.

There are different variations of neural networks:

a. Artificial Neural Network: ANNs are intricate networks of computer processors, drawing inspiration from biological nervous systems. These systems facilitate the connection of dental healthcare professionals worldwide. The first layer is the input layer. The inputs are processed only in the forward directions. The subsequent layer is termed the hidden layer, comprising neurons. Data from the input layer is transmitted to the hidden layers, traversing through each hidden layer sequentially. The third layer constitutes the output layer, where the results are ultimately consolidated and presented.

b. Convolution Neural Network: CNN, a prevalent deep learning model utilized for image recognition and generation, diverges from ANN through the incorporation of convolution layers alongside pooling and fully connected layers within the hidden layers. It represents a distinct subset of deep learning, primarily employed for image processing and the analysis of radiological datasets.

c. Generative Adversarial Networks (GAN): GAN, a deep learning technique introduced by Goodfellow et al. in 2014, is an unsupervised learning approach crafted to autonomously unearth patterns from input data and produce new data bearing similar features or patterns to the input data. GAN is composed of two neural networks: a generator and a discriminator. The generator's ultimate purpose is to produce data that is indistinguishable from the original input data. The discriminator aims to discriminate between generator generated and original input data to the greatest extent possible.

3. Deep Learning: Deep learning relies on multiple layers of processing, hence the term "deep," to explore representations of data through one or more layers of abstraction. In this algorithm, multiple layers are employed to identify simple features like lines, edges, and textures, progressing to more complex shapes, lesions, or entire organs within a hierarchical structure.[9]

Application of AI in Prosthodontics:

Role in cad/cam

Digital technologies like CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) have been recommended for creating fixed dental prostheses and complete denture prostheses. Incorporating AI into the CAD system can notably decrease lead times and establish a knowledge-based design environment. In hospital settings, AI-based CAD is being integrated into clinical practices alongside Picture Archiving and Communication Systems (PACS) to enhance workflow. Model-Based Reasoning (MBR) is the process by which CAD can be integrated with AI. It examines both qualitative and quantitative aspects to anticipate the interactions of design components. MBR relies on models and derives insights from previous behaviors.
Some examples of AI integrated CAD software are-

1. SOLIDWORKS- owned by Dassault Systems Company, has introduced xDesign, which utilizes AI as a tool for drawing and extruding in engineering design tasks. The user begins by creating the model and setting constraints. Once the necessary specifications are established, SOLIDWORKS xDesign leverages AI integrated within its system to instantly generate the part based on the defined constraints.

2. NETVIBES One Part- developed by Dassault Systems Company, exemplifies AI-enabled design software. This tool provides a straightforward solution for reusing components to increase efficiency. With NETVIBES One Part, operators can easily access 2D/3D components with just a few clicks.

3. Artificial Intelligence (AI) Denoiser- developed by NVIDIA, is a tool that harnesses AI and machine learning to provide users with immediate interactive feedback, enabling them to make more informed decisions. It rapidly generates noise-free images through GPU-accelerated AI. Known as the fastest and most straightforward picture visualization tool currently on the market, AI Denoiser sets a new standard for efficiency.[10]

Role in 3d printing:

Additive Manufacturing (AM), also known as 3D printing, is a fabrication technique that builds parts layer by layer, allowing for the creation of components with intricate geometries and properties that vary gradually across the structure. Machine Learning techniques are presently employed to address challenges in the pre-manufacturing stage of Additive Manufacturing. This involves generative methods and trial processes. Additionally, other aspects related to enhancing the efficiency of design and manufacturing for 3D printing techniques include printability assessment, accelerated slicing, nozzle path planning, cloud service platforms, service assessment, and security measures for detecting attacks. The design feature database offers ideas and design elements for less experienced designers. Utilizing Machine Learning techniques in 3D printing allows for feature recommendations to be applied to existing CAD models, thereby assisting designers in accelerating the decision-making process during the design stage.[11]

Role in Fixed Dental Prosthesis:

Tooth Preparation

Even for specialists with extensive clinical experience, preparing teeth for a crown or bridge can present challenges. Dentists are attracted to the concept of employing robotic devices for tooth preparation due to their practicality.

Components of robotic system are as follows:

1. Laser scanner: Capture 3D data of the patient's target tooth, adjacent teeth, opposing teeth, and the teeth fixture.
2. Computer-aided design (CAD) / computer-aided manufacturing (CAM) software: Design the target preparation shape and generate a 3D motion path for the laser.

3. Laser generator: Employ an effective low-heat ultra-short pulse laser (USPL) generator to produce USPL beams suitable for hard tissue preparation.

4. Laser guiding arm: Utilize a 6-degree-of-freedom robot arm to accurately guide the laser beam towards the robotic device.

5. Tooth fixture: Connect the robotic device with the target tooth and safeguard adjacent teeth from laser cutting. This fixture is designed using SolidWorks software.

The Geomagic Qualify software is employed to assess the overall form accuracy by comparing the 3D data of prepared teeth with the original CAD data of the target shape. The mean error is then calculated.[12]

Dental Implantology

Dynamic computer-navigated systems provide freehand implant navigation utilizing highly precise motion-tracking technology. This technology monitors the positions of both the dental drill and the patient throughout the surgery. Robotic surgery offers sustained precision, enhanced stability, improved efficiency, and increased flexibility in assisting with dental implant preparation and implantation. Boesecke and colleagues (Medical Intelligence, Schwabmünchen, Germany) introduced the initial study on robot-assisted dental implantation aimed at reducing errors in 2002.

There are 2 robotic systems for dental implantology namely:

1. YOMI: Neocis Inc., based in the USA, developed the first commercially available and cutting-edge robotic system for dental implantology, known as Yomi. It received FDA approval in 2017 (U.S. Food and Drug Administration, 2017). Yomi is a computerized navigation system designed to aid in both the planning (pre-operative) and surgical (intra-operative) stages of dental implantation surgery. It allows dentists to seamlessly integrate digital imaging from preoperative planning into their operating environment using haptic robotic technology. YOMI provides tactile guidance by restricting the drill's position, orientation, and depth, eliminating the necessity for a custom surgical guide and concurrently preventing any deviation of the surgeon's hand (Fig 1).[13]

2. ZHAO: In late 2017, Zhao unveiled the world's first autonomous dental implant placement system, boasting high autonomy, continuous intraoperative adjustments, and the ability to perform surgical tasks directly on patients without visible surgeon control.

Fig 1: YOMI

Role in Removable Prosthesis:

Teeth Arrangement Robots:

The conventional method of producing denture systems has been supplanted by robotic production. The dimensions, positioning, and orientation of each tooth relative to others, as well as the curvature of the dental arch, vary significantly among complete dentures. The operational flexibility of a robot is advantageous, as it can be adjusted to accommodate the manufacture of complete dentures.[14]

A single-manipulator robotic system for the arrangement of complete denture teeth comprises the following components:

- Light-sensitive glue (Wang and Li. 2001)
- Light source device
- Denture base
- Control and motion planning
- Robot modulation software for arranging tooth and a core control system having tooth-arrangement
- Computer
- Electromagnetic gripper
- 6-Degree of freedom Cloud-based Robotic system robot
- A significantly enhanced tooth arrangement robotic system with 50 degrees of freedom (DOF) was subsequently developed. This system features 14 independent manipulators, a dental arch generator, and a slipway mechanism as its key components (Zhang et al., 2011; Zhang et al., 2010).
- The dental arch generator shapes the dental arch curve to align with that of the patient's oral cavity.
- The slipway mechanism is employed to regulate the dental arch generator.

Role of AI in Estimation of Vertical Dimension of Occlusion in Completely Edentulous Patients:

The vertical dimension of occlusion (VDO) pertains to the height of the lower part of the face when the upper and lower dental arches are in centric occlusion. Lateral cephalometric radiographs of the patients were obtained using the "FONA XPAN DG" scanner (FONA S.r.l, Galilei 11 - 20090 Assago, Italy). In the lateral cephalometric images, the Anterior Nasal Spine (ANS) and Menton (Me) landmarks were utilized to establish the Vertical Dimension of Occlusion (VDO). Dentures were crafted according to the lower anterior facial height determined through the analysis derived from the aforementioned cephalometric platform. A.I. digitization of the image is conducted to automatically identify and trace the landmarks. Following image calibration, cephalometric analysis is performed based on the McNamara method to automatically determine the ANS-ME distance.[15]

Role in Maxillofacial Prosthesis:

i. Bionic Eye:

A bionic eye, also referred to as a retinal prosthesis, is an electronic device designed to emulate the functionality of the retina. It offers vision to individuals experiencing severe vision loss (Fig 2). Three types of bionic eye includes retinal implants, cortical implants and optic nerve implants.

The retina, situated at the back of the eye, is a thin tissue layer containing specialized cells known as photoreceptors. These cells convert light into electrical signals, which are then transmitted to the brain and interpreted as visual images. In individuals with retinal damage, the photoreceptor cells lose their functionality, leading to vision impairment. Retinal implants function by circumventing the damaged photoreceptors and directly stimulating the remaining healthy cells within the retina. These implants comprise a minuscule array of electrodes implanted into the retina. Connected to a small camera mounted on glasses worn by the patient, these electrodes receive signals from the camera and transmit them to a compact computer worn by the patient. The computer processes the images and sends signals to the electrodes in the implant. Upon stimulation, these electrodes generate small electrical currents, activating the healthy cells in the retina. Subsequently, these cells transmit signals to the brain, where they are interpreted as visual images.

The quality of visual images generated by retinal implants can significantly differ based on various factors, such as the quantity and positioning of electrodes, the camera's resolution, and the computer's processing algorithms.[16]

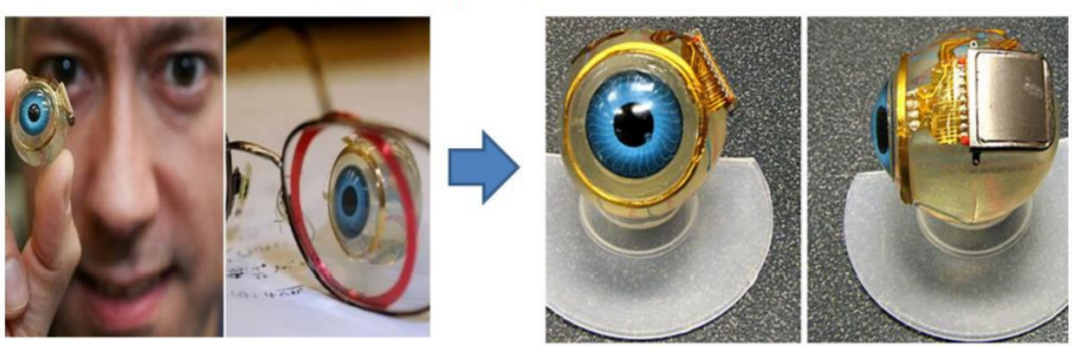

Fig 2: Bionic Eye

ii. Artificial Skin:

The skin, encompassing an expansive area of approximately 2 square meters, serves as the body's largest organ. It safeguards us from external elements, regulates homeostasis, including body temperature, and facilitates the sense of touch. This motivates scientists and engineers to create flexible and stretchable electronic devices or systems that mimic the capabilities of human skin, termed electronic skin (e-skin).[17]

Significant strides have been taken in the advancement of electronic skin (e-skin):

- Material innovations
- focus on enhancing sensing capabilities, such as stretchability, sensitivity, and long-term monitoring.
- Emphasis is placed on creating user-friendly detection modes, including noninvasive, inflammation-free, gas-permeable, and implantable methods.
- System-level integration addresses aspects like data transmission and power supply.
- Efforts are directed towards realizing new functionalities, such as self-healing capabilities.

iii. Maxillofacial Prostheses Coloration:

The L*, a*, and b* values corresponding to human skin were obtained by measuring the skin color between the first and second metacarpal bones using a spectrophotometer. These L*, a*, and b* values served as input data for the deep artificial neural network (ANN). The output data consisted of pigment parameters indicating the amounts of white, red, yellow, and blue compounds. The color differences between the actual skin color of the research participants and the validation specimens were assessed using the E00 color system. E00 values were calculated to compare the real skin color of the research participants with the validation specimens (Fig 3).
The deep ANN method attained a lower DE00 value, indicating better color matching compared to the random forest algorithm. An advantage of this deep ANN approach is its feasibility for execution on a personal computer with an average CPU. Employing deep ANN for prosthesis coloration presents a promising technique for enhancing the overall success of maxillofacial prostheses rehabilitation.[18]

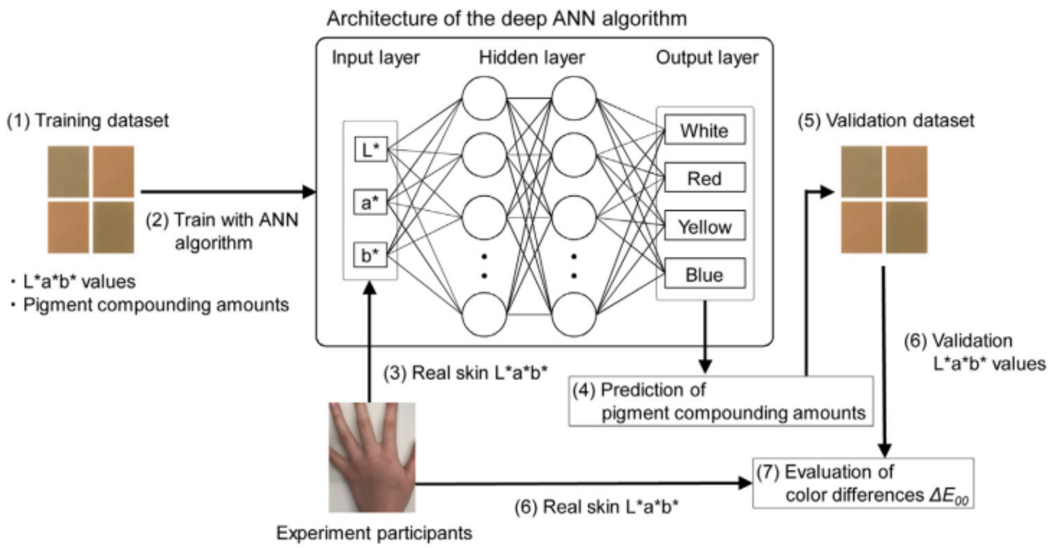

Fig 3: Schematic illustration of maxillofacial prosthesis coloration

Limitations

1. AI-based systems, being machine-driven and developed by computer scientists without medical training, often adopt a problem-oriented approach in healthcare delivery.
2. Moreover, AI cannot fully replace contemporary healthcare delivery models, which heavily rely on clinician skills and patient-clinician communication.
3. Robotic systems are intricate and demand expertise for their effective operation and performance.

Future Scope

While literature suggests that AI in dentistry enhances precision, repeatability, and reliability, research in robotic dentistry is limited due to the scarcity of readily available systems. Furthermore, there is a lack of expertise in programming and controlling robotic systems. As a result, progress in this field relies on successful collaboration between dentists and engineers. However, this may change soon as the robotics community explores novel communication strategies and programming approaches. Furthermore, conducting research on dental educational robotics within university settings holds promise as a means to introduce robotic dentistry and overcome barriers to acceptance of robotic systems among future dentists.[14]

CONCLUSION

Artificial intelligence has brought significant changes to both medicine and dentistry. While AI systems offer considerable advantages in dentistry and dental education, it's important to recognize that the human biological system is complex. These technological advancements represent novel discoveries by humans. Additionally, while AI can assist clinicians in performing tasks proficiently, it cannot replace the intellect, knowledge, skill, and treatment planning capabilities of humans. All robot applications discussed in this article, from teeth arrangement for complete dentures to dental material testing or tooth preparation, possess inherent potential to propel dentistry into a new era where digitalization aids in managing real-world scenarios. Overall, the technological readiness level remains relatively low, and further research is necessary to fully realize the value of robotic dentistry. Therefore, the pace of research in this field should accelerate in the coming years.

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