Transformative Impacts of Artificial Intelligence (AI) and Extended Reality (XR) on Biomedical Engineering (BME): Innovations, Implications, Challenges, Opportunities

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Abstract: The convergence of Artificial Intelligence (AI) and Extended Reality (XR) has heralded a new era in the field of Biomedical Engineering, offering unprecedented avenues for innovation, diagnostics, treatment, and education. This research delves into the symbiotic relationship between AI and XR, unraveling their collective potential to revolutionize healthcare practices. AI, characterized by its ability to learn and adapt, has transcended its role within data analysis to become an indispensable tool in healthcare. Through advanced algorithms, AI can predict disease patterns, enhance medical imaging, and optimize treatment protocols. On the other hand, XR technologies, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), immerse users in virtual environments, facilitating interactive and experiential learning and treatment methods. This research focuses on the study that inspects with the integration of AI and XR in biomedical applications, illuminating their role in diagnosis, treatment, and training. AI-driven image analysis augments medical imaging, expediting disease identification and tracking treatment progress. XR, through its immersive nature, empowers surgeons with detailed anatomical insights during procedures and aids in rehabilitation through engaging simulations. The synergistic marriage of AI and XR also redefines medical education by offering immersive training experiences to healthcare practitioners and bridging the gap between theory and practice. Furthermore, ethical considerations and challenges emerge as these technologies evolve. Privacy concerns, data security, and the need for regulatory frameworks are paramount in this dynamic landscape. Striking the right balance between innovation and patient safety remains an imperative task. In the context of this research, the fusion of AI and XR from a biomedical engineering perspective holds the potential to revolutionize healthcare. As AI refines diagnostics and treatment strategies, XR provides a tangible platform for immersive experiences that enhance training and therapeutic interventions. This research navigates the landscape of this transformative convergence, shedding light on its profound implications for Biomedical Engineering and the well-being of patients worldwide.

Keywords: Artificial Intelligence (AI), Bioinformatics, Biomedical Engineering (BME), Biomedical image processing, computer vision, Extended Reality (XR), Deep Learning (DL), healthcare informatics, Machine Learning (ML), Mixed Reality (MR), Virtual Reality (VR).

1. Introduction

In the ever-evolving landscape of healthcare, the convergence of Artificial Intelligence (AI) and Extended Reality (XR) has emerged as a transformative force, heralding a paradigm shift within the realm of Biomedical Engineering [1]. This interdisciplinary junction promises to reshape how medical diagnostics, treatments, and education are approached, fostering a new era of innovation with profound implications for patient care. The synergy between AI and XR has paved the way for unparalleled opportunities in precision medicine and experiential learning, where the amalgamation of intelligent algorithms and immersive virtual environments holds the potential to redefine the boundaries of possibility. This research context dives deeper into that revolutionary intersection, embarking on a comprehensive exploration from a Biomedical Engineering perspective to uncover the intricacies, potentialities, and challenges that arise at the confluence of these cutting-edge technologies [2, 3]. Through a meticulously designed mixed-methods approach, encompassing both quantitative analysis of AI algorithm performance and qualitative investigation of biomedical engineering application device peripheral perspectives, this research also aims to illuminate the pathway towards harnessing the collaborative power of AI and XR in shaping the future of healthcare delivery and education. As AI evolves into a diagnostic powerhouse and XR materializes as an immersive learning platform, the impact on Biomedical Engineering is poised to be nothing short of revolutionary, sparking a wave of advancements that transcend the boundaries of traditional medical practices.

2. Methods and Experimental Analysis

This research employs a mixed-methods approach to explore the intersection of Artificial Intelligence (AI) and Extended Reality (XR) from a Biomedical Engineering perspective. The quantitative analysis involves utilizing state-of-the-art AI algorithms to analyze medical imaging datasets, assessing their diagnostic accuracy and treatment optimization capabilities. On the other hand, the qualitative investigation involves gathering informative data from various types of healthcare professionals and surveys with a broader audience to gather insights into the practical implications and challenges of integrating AI and XR in healthcare. The implementation process includes developing AI algorithms using machine learning techniques and creating XR applications using relevant software tools. Next, the data analysis encompasses quantitative evaluation of AI algorithm performance and qualitative thematic analysis of a diversity of informative data collections and survey responses. Afterwards, all the ethical considerations are also addressed through proper consent procedures and data privacy measures. The context of this research aims to contribute to the understanding of how the synergy between AI and XR can reshape Biomedical Engineering practices, while acknowledging potential limitations such as dataset availability and algorithm biases.

3. Background Research and Available Knowledge

First, let's begin with and dive into the technical accelerated computing perspective within the realm towards AI. Artificial intelligence (AI) represents the intelligence exhibited by machines and software systems, distinguishing it from human and animal intelligence. AI finds applications in diverse domains, including advanced web search engines like Google Search, recommendation systems employed by platforms like YouTube, Amazon, and Netflix, voice recognition technology as seen in Siri and Alexa, self-driving vehicles such as Waymo's cars, generative tools like ChatGPT and AI-generated art, and excelling in strategic games such as chess and Go. The roots of AI as an academic discipline trace back to its establishment in 1956. Its historical trajectory has been marked by cycles of optimism followed by periods of disillusionment and reduced funding.

However, the field experienced a resurgence after 2012, driven by the success of machine and deep learning techniques that surpassed prior AI approaches, leading to a significant influx of funding and heightened interest. AI research encompasses a spectrum of sub-fields, each focusing on specific objectives and employing distinct methodologies. Traditionally, AI research has centered around goals such as reasoning, knowledge representation, planning, learning, natural language processing, perception, and robotic support. Among the overarching aspirations of AI is achieving general intelligence, denoting the ability to solve a wide array of problems. Addressing these objectives has necessitated the integration of diverse problem-solving techniques, including search algorithms, mathematical optimization, formal logic, artificial neural networks, and statistical, probabilistic, and economic methods. AI is not confined to the boundaries of computer science but draws insights and inspiration from a wide range of plethora from many disciplines, encompassing psychology, linguistics, philosophy, neuroscience, and various other fields. This multidisciplinary approach underscores the complexity and interconnectedness of AI's evolution and its journey towards achieving human-like intelligence in machines [1–15].

Next, let's dive deeper into the perspective revolving around the domains of BME. Biomedical Engineering (BME), also referred to as medical engineering, is a dynamic field that applies the principles of engineering and design concepts to the realms of medicine and biology, with the primary objective of advancing healthcare through diagnostics, therapy, and patient care. This interdisciplinary discipline not only leverages engineering expertise but also integrates logical sciences to devise innovative solutions that improve medical treatments and outcomes. The role of a biomedical engineer encompasses diverse responsibilities, extending to the management of medical equipment in healthcare settings while ensuring adherence to industry standards. This involves tasks such as equipment procurement, routine testing, preventive maintenance, and offering recommendations for equipment enhancement, a role often termed Biomedical Equipment Technician (BMET) or clinical engineering [16–20]. Biomedical engineering has evolved as a distinct field, transitioning from being an interdisciplinary specialization to establishing its own domain. This evolution mirrors the trajectory of many nascent disciplines. The core of biomedical engineering activities revolves around research and development, spanning a wide array of subfields. These subfields encompass various areas such as medical device innovation, biocompatible prostheses, diagnostic tools, therapeutic devices ranging from macroscopic clinical equipment to micro-implants, widely used imaging technologies like MRI and EKG/ECG machines, the exploration of regenerative tissue growth, and the advancement of pharmaceutical drugs and therapeutic biologicals [21–23]. In essence, biomedical engineering serves as a bridge between cutting-edge engineering principles and the intricate world of healthcare. This field's trajectory involves the synthesis of innovation, technology, and biology to create solutions that enhance patient care, diagnose ailments more accurately, and devise novel methods of treatment. The spectrum of applications within biomedical engineering underscores its profound impact on modern medicine and its instrumental role in shaping the future of healthcare delivery [24, 25].

Now let's go into the knits and grits of the virtual environments and their associated extensions of XR. Extended reality (XR) is the term that primarily refers to the realms of augmented reality (AR), virtual reality (VR), mixed reality (MR). This technology is mainly intended to either combine or mirror the physical world aspect with a ***"digital twin world"*** where the user is capable of interacting with its environment. The surge in development and adoption of virtual, augmented, and mixed reality (VR, AR, and MR) devices has been a defining trend since 2010, with their applications spanning commercial, educational, and biomedical sectors. While the concept of virtual reality has historical roots dating back to the 19th century, it gained traction in the 1990s due to advancements in hardware and computer graphics. However, technical limitations such as bulky headsets, slow computers, and side effects like motion sickness hindered its progress during the 2000s [26–28].

In the recent years, there has been a resurgence of interest in VR technology. Modern VR devices like the Oculus Rift, Google, HTC, Valve, and Samsung headsets offer enhanced fields of view, improved frame rates, and reduced motion sickness effects. Alongside VR, augmented reality (AR) and mixed reality (MR) experiences have also gained momentum. The Microsoft HoloLens, a pioneering MR device, was introduced in 2016, enabling untethered mixed reality experiences. AR became more widespread with the release of games like Pokémon GO in 2016.

However, commercialization of AR glasses has been limited due to cost considerations. Despite the popularity of these extended reality (XR) devices, a comprehensive analysis of their impact on biomedicine, surgery, and medical education is necessary. This research addresses this gap by defining VR, AR, and MR concepts and functionalities. It highlights the current biomedical trends in XR, including visualization, clinical care, and research. The use of XR in interactive educational platforms is exemplified, and case studies demonstrating its applications are provided [29–36]. This research also discusses the challenges, complexity, and cost associated with existing XR platforms. This thorough overview aims to inform biomedical and medical professionals about the potential of XR technologies, opening avenues for interactive educational and discovery projects within the field. As XR devices continue to shape the landscape of healthcare and education, understanding their capabilities and applications becomes pivotal for leveraging their benefits effectively.

4. The Potential of XR within the Medical Domain

The integration of Extended Reality (XR) technology into the medical field has brought forth a plethora of opportunities, revolutionizing healthcare practices and benefiting medical professionals in multifaceted ways. This transformation is evident through the reduction of time required for surgeons to gather critical information before making crucial decisions. XR solutions, by immersing surgeons in relevant data, hold the potential to enhance decision-making within the operating room. Furthermore, XR's applications extend to training new medical practitioners and facilitating their understanding of patients' conditions, leading to more empathetic and effective care [37–45]. The utilization of XR in healthcare is varied and impactful in various retrospectives. To better understand the concept and functionality capabilities figure 1 provides a visual representation concerning the matter.

Patient Understanding and Pain Relief: XR has the potential to alleviate patients' pain by immersing them in virtual experiences during treatment. For instance, virtual reality games have been designed to engage cancer patients during therapy sessions, offering distraction and relief from discomfort. By allowing doctors to undergo similar experiences as their patients, XR fosters a stronger sense of empathy and trust, thus enhancing the doctor-patient relationship.

Surgical Training and Simulation: Immersive technology plays a pivotal role in training healthcare professionals for surgery. Surgical simulators developed using XR enable medical practitioners to practice surgical procedures without requiring live patients, cadavers, or animals. Such simulators provide a safe environment for surgeons to refine their skills and techniques before performing actual surgeries. Additionally, 3D models generated from patient images, combined with XR immersive headsets, empower surgeons to visualize and plan complex operations more effectively.

Preoperative Preparation: XR opens limitless possibilities in healthcare, particularly in surgical training and planning. Realistic 3D models created from patient data aid surgeons in familiarizing themselves with intricate anatomical structures and practicing surgical maneuvers. An immersive XR platform can also facilitate collaboration among surgeons, allowing them to plan and discuss procedures more efficiently. Surgeons can experience the tactile sensations of using surgical instruments through XR applications, thus enhancing their preparedness before surgery.

Medical Education and Training: The impact of XR in medical education is significant, enabling medical students and doctors to explore anatomically accurate 3D models of the human body. XR-based educational apps enhance the learning experience by providing an immersive environment for observing intricate anatomical details and practicing surgical skills. This immersive learning approach enables medical professionals to gain a deeper understanding of various systems and enhance their surgical expertise.

Diagnosis and Health Assessment: XR applications can revolutionize patient diagnosis by allowing medical professionals to scan patients' bodies and identify health issues in real-time. These technologies employ 3D models and immersive experiences to detect ailments, fractures, and even cancers. Patients can be educated about their impending surgeries through step-by-step visualizations created from XR programs. The adoption of the XR technologies in the medical field presents a transformative shift in healthcare practices. By facilitating immersive training, precise diagnosis, enhanced patient understanding, and collaborative surgical planning, XR has the potential to reshape the way medical professionals interact with data, patients, and procedures. As XR's applications continue to evolve, its integration promises to elevate the standards of medical care, education, and patient outcomes.

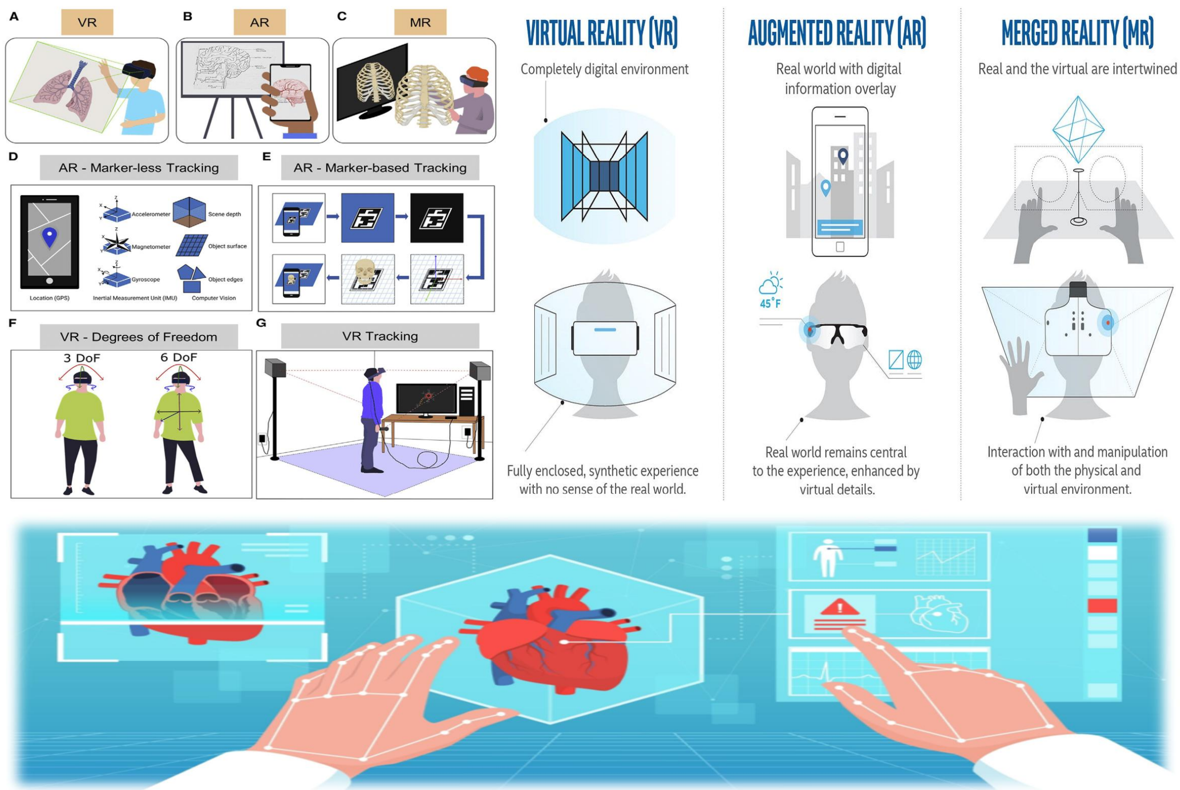

Figure 1. A visual representation of XR in medical systems.

5. AI-XR Applications Advancement and Innovations

The convergence of Artificial Intelligence (AI) and Extended Reality (XR) has yielded a multitude of applications, spanning various sectors such as medical training, armed forces training, gaming, robotics, and advanced visualization. In each of these categories, the amalgamation of AI and XR has brought about transformative opportunities and solutions, addressed diverse challenges and enhanced user experiences. The applicability of AI-XR with its global statistics are provided in figure 2 for an illustrative design view and visual representation.

Medical Training: Combining AI and XR has unlocked new dimensions in medical training. XR offers immersive, risk-free environments, aiding trainees in tasks like surgical procedures. To harness the potential of XR data and evaluate user skills, AI techniques are employed. By extracting and selecting features from XR-generated data, AI algorithms objectively assess user performance, thereby enhancing training effectiveness. The combination of these technologies has led to the creation of virtual patients, allowing medical students to practice diagnostic interview skills in natural interactions.

Armed Forces Training: AI's role as an agent in interactive virtual environments has redefined armed forces training. AI agents are designed to challenge participants at their skill levels, adapting their behavior accordingly. Utilizing Gaussian process Bayesian optimization techniques, AI agents enhance their performance through interactions with intelligent adversaries. This AI-AI interaction within XR environments enables effective armed forces training, preparing participants for dynamic scenarios.

Gaming Applications: AI-XR synergy has revolutionized gaming, allowing AI agents to engage in complex games like Starcraft II and Dota 2. These applications offer challenging environments to rapidly train and test AI algorithms. Furthermore, AI agents become integral non-player characters, interacting with users within gaming environments. Despite challenges like non-adaptive AI adversaries, AI-XR combinations are pushing the boundaries of gaming experiences.

Robots and Autonomous Cars: The fusion of AI and XR addresses challenges in designing robots and training autonomous cars. Extracting features from sensor data and modeling interactions with the environment are formidable tasks. Virtual environments offer a cost-effective solution for training AI, enabling robots and autonomous cars to learn complex tasks without prior knowledge. Reinforcement learning (RL) techniques within XR empower AI-driven robots and cars to thrive in real-world scenarios.

Advanced Visualization: AI-XR integration extends to advanced visualization, enhancing understanding of intricate structures and systems. AI-powered imaging algorithms optimize XR displays by automatically visualizing target structures. This synergy facilitates complex anatomical visualization for medical applications and even supports deep learning structure visualization. The combination of AI-driven algorithms and XR platforms enriches advanced visualization, making it accessible and intuitive.

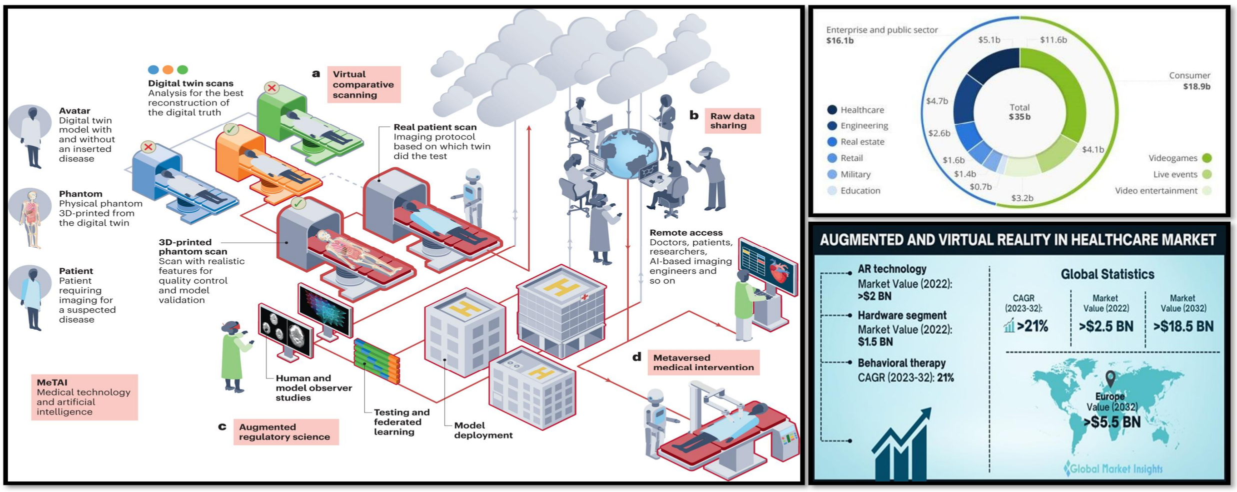

Fig. 2. An illustration design view of AI-XR applicability and global stats.

The synergy between AI and XR has propelled a diverse range of applications across industries. Medical training benefits from XR's immersive environments, armed forces training gains adaptability through AI-XR interactions, gaming experiences are enriched with AI agents, robots and autonomous cars are trained in cost-effective virtual environments, and advanced visualization becomes more accessible with AI-enhanced XR displays. The fusion of AI and XR continues to redefine possibilities, shaping the landscape of these domains and setting the stage for innovative advancements [37–45].

6. An Overview of AI-XR from Health Professionals

The information retrieved from various professional on ***"Extended Reality in Healthcare: Research and Applications"*** offers insights into the intersection of Extended Reality (XR) and healthcare, catering to readers with an interest in the merging of these domains. While the reviewing audience primarily encompasses extended reality technologists, biomedical engineers, instrumentation and measurement experts, computer scientists, and healthcare professionals, the content's alignment with the stated promise of an in-depth introduction to XR and its potential in healthcare varies across different intakes. The short few comprises 15 categories, retrieved by a diverse group of 34 individuals, with two of them being among the main four medical domains. The initial few outline the foundational concepts of XR, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), alongside their applications and platforms. The overview of these technologies sets the stage for the subsequent usage and applicability. Next, a specific few addressing clinical applications of XR delve into broad areas such as mental health, pain management, and physiotherapy. However, some audience seem to lack a direct link to the concept core theme. For instance, discussions on innovative telehealth systems are included, but the relevance to XR in healthcare is at times tangential. The overview of telemedicine's history and its amplified role during the COVID-19 pandemic might appear disconnected from the XR focus. Some individuals provided valuable insights, especially where XR's potential aligns closely with healthcare needs. As many were discussing XR's impact on patient recovery, wellness, and clinical skills development present a more detailed exploration of XR applications, albeit drawing from existing literature and patents. Virtual reality's role in medical education and patient-focused education is also elaborated, highlighting the technology's potential for immersive and interactive learning experiences. The selected few also occasionally delves into emerging technologies, such as the fusion of XR and artificial intelligence (AI) to enhance telehealth and training. The professionals on the evolution and contribution of XR in smart healthcare systems offers a comprehensive exploration of the synergy between XR, AI, and data-centric healthcare approaches. They also mentioned that, aligned with the techniques overarching theme, showcases XR's role in creating intelligent healthcare solutions. While some people might be perceived as tangential, the wide range of individuals ultimately provides a range of perspectives on XR's potential in healthcare. The discussions span from clinical applications and patient wellness to medical education and beyond [37–45]. Despite occasional deviations, the info remains valuable for readers aiming to grasp the growing relationship between XR and healthcare, especially when exploring XR's integration with AI, data analytics, and evolving healthcare paradigms.

7. Biomedical VR-AR Case Studies Analysis and Costings

The provided case studies offer a comprehensive exploration of the integration of Extended Reality (XR) in various biomedical applications, showcasing the versatility and potential of XR technologies in the healthcare field. ***Case Study 1*** highlights the application of XR in visualizing complex protein images within single cells. The utilization of Head-Mounted Displays (HMDs) and VR applications provides a platform for immersive 3D visualization. ConfocalVR, a software developed by Immersive Science, stands as an example of a tool enabling users to comprehend cellular architecture and protein distribution through immersive visualization. The investigation study employs 3D subcellular co-detection by indexing (CODEX) images obtained through multiplex imaging of cellular markers. The high-resolution CODEX datasets are visualized using ConfocalVR, offering a deeper understanding of cellular structures and distributions.

Case Study 2 delves into the application of Augmented Reality (AR) in neurosurgical planning and execution. AR's potential is showcased in the visualization of presurgical neurovascular anatomy, aiming to improve outcomes in interventions involving the head, neck, and spine. An illustrative example focuses on spine fixation, where AR surgical navigation (ARSN) techniques were employed for screw placements. This exploration demonstrates that AR-based navigation led to higher accuracy in screw placement and a reduced proportion of cortical breaches, thus enhancing the precision of spine fixation procedures.

Case Study 3 presents a case involving Virtual Reality (VR)-based surgical techniques for complex cardiac repair. In this instance, VR technology was applied to visualize complex cardiac anatomy and surgical strategies for a patient with heart failure and a congenital cardiac anomaly. The VR environment allowed the surgeon to manipulate computational models of both typical and altered cardiac anatomy, facilitating enhanced spatial comprehension and planning for surgical interventions. This case demonstrates how VR can serve as a valuable planning tool for intricate surgical scenarios.

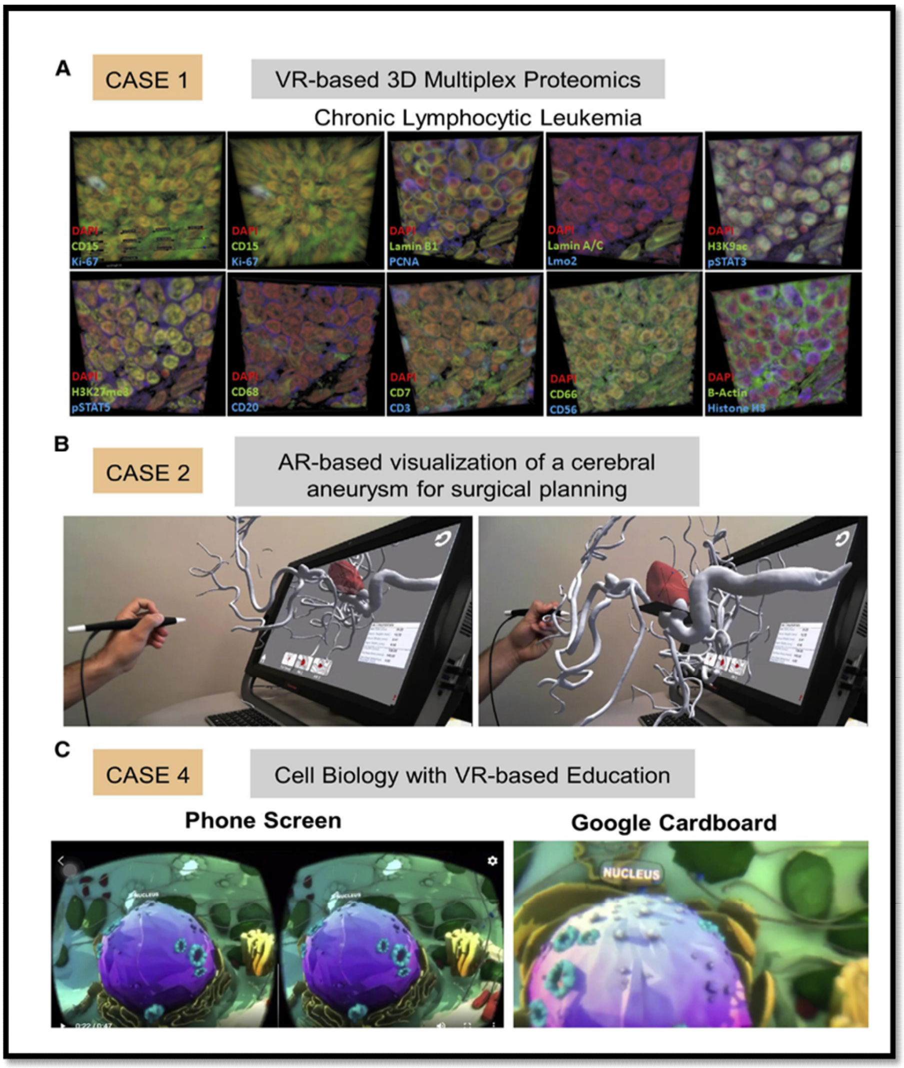

Fig. 3. A Visual Representation of the Case Studies

Case Study 4 introduces the use of Google Cardboard as a cost-effective means to experience VR in educational settings. This case exemplifies how Google Cardboard, a simple VR viewer for smartphones, can be used to create many immersive learning environments. The case study 4 experiments involved utilizing Google Cardboard to view a 360-degree video depicting the organelles within a plant cell, providing an engaging and educational experience for learners.

To give an idea an concerning the investigation analysis Fig. 3 provides a visual representation of the case studies involved for the conduction of the exploration research studies and their design illustrations. Collectively, these case studies underscore XR's broad applicability in healthcare, ranging from visualizing cellular structures to enhancing surgical planning and medical education. The diversity of these applications highlights the potential of XR to revolutionize various aspects of the healthcare industry, offering improved visualization, training, and procedural accuracy.

The implementation of Extended Reality (XR) technologies in biomedical applications encompasses a wide range of complexities and costs. The diversity in implementation methods allows for flexibility in accommodating various needs and resources. At the more accessible end of the spectrum, there are options like using Google Cardboard hardware paired with open-source software like Blender. This combination enables users with basic programming/scripting skills to create affordable VR experiences. Conversely, at the higher end of complexity and cost, specialized XR platforms tailored for specific medical applications can demand significant investment, often reaching tens of thousands of dollars.

To facilitate exploration and decision-making within this diverse landscape of XR implementation, Fig. 4 offers a very useful overview of commercially available solutions. The data is structured based on cost categories: no/low cost, prosumer, and professional/commercial. Each of these cost categories is further subdivided into three implementation types: software only, hardware only, and complete platform solutions that encompass both hardware and software components. This classification system allows individuals and organizations to identify XR solutions that align with their specific needs and available resources. Whether seeking affordable entry points into XR technology or aiming for advanced and comprehensive solutions, this illustration serves as a starting point for discovering and comparing various options.

Depending on the chosen route, specific skill sets such as programming and 3D modeling might be required, emphasizing the importance of selecting an approach that suits both technical capabilities and the desired outcome. In essence, the range of XR implementation strategies outlined in the designed figure underscores the democratizing potential of these technologies. From budget-friendly options that enable modest customization to sophisticated platforms designed for professional and medical applications, XR offers a diverse array of solutions that can be tailored to meet the unique demands of biomedical contexts.

Type	XR type	Product name	Company	Information
No-cost to low-cost solutions				
Software	AR/VR/MR	Unity[a,b]	Unity Technologies	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	AR/VR/MR	Unreal[a,b]	EPIC Games	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	AR/VR/MR	WebXR Device API[b]	Immersive Web Working Group at the W3C	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	AR/VR	Sketchfab[a,b]	Sketchfab	no programming experience needed
	AR/VR/MR	Blender[b]	Blender Foundation	benefits from programming and 3D modeling experience
	MR	HoloAnatomy	Case Western Reserve University	no cost for software but requires Microsoft Hololens
Hardware	VR	Google Cardboard (or do it yourself [DIY] Viewer)[b]	Google/DIY	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	VR	Gear VR[b]	Samsung	requires programming knowledge or additional software packages to develop/implement biomedical solutions
Platforms	N/A	None readily identifiable	N/A	N/A
Prosumer solutions				
Software	VR	DICOM2Print	3DSystems	utilizes a VR or MR HMD
Hardware	VR	Vive[b]	HTC	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	VR	Oculus hardware[b]	Facebook	hardware at time of publication includes Oculus Quest, Quest 2, and Rift
	VR	Reverb[b]	HP	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	VR	Index[b]	Valve	requires programming knowledge or additional software packages to develop/implement biomedical solutions
	AR	Google Glass[b]	Google	requires programming knowledge to develop/implement biomedical solutions
	AR	Apple Glasses[b]	Apple	requires programming knowledge to develop/implement biomedical solutions
	MR	zSpace[b] (monitor)	zSpace	requires programming knowledge or additional software packages to develop/implement biomedical solutions; NB (note well): the zSpace product does include software at acquisition but cannot readily be used for biomedical solutions
Platforms	VR	Enduvo	Enduvo	Platform is compatible with SteamVR tracking-based VR systems (e.g., Vive, Vive Pro, and Valve Index), Windows MR VR systems, and Oculus VR systems
	VR	Elucis	Realize Medical	Platform is compatible with SteamVR tracking-based VR systems (e.g., Vive, Vive Pro, and Valve Index), Windows MR VR systems, and PC-based Oculus VR systems
Production/commercial solutions				
Software	MR	SyngoVia	Siemens	utilizes Microsoft Hololens
Hardware	N/A	none readily identifiable	N/A	N/A
Platforms	MR	True 3D	EchoPixel	utilizes zSpace monitor
	VR	PrecisionVR	Surgical Theater	platform service includes on-site VR specialist
	VR	SimX	SimX	platform is intended for simulation/training.

This illustrates the commercially available solutions for XR technologies. The value is stratified initially by start-up cost and secondarily by whether the product is software, hardware, or a platform (a combination of hardware and software). The list is not intended to be exhaustive. Currently, a no-cost to low-cost solution is below $200 for an initial investment. Production/commercial solutions exceed $5,000 (often the limit for organizations' capital investment cost).

a Cost is affected by the type of license (i.e., personal versus commercial use).
b The Solutions are not designed nor marketed solely for any biomedical use. Implementations can be created that target biomedical and medical applications.

Fig. 4. A Representation of the Costing Analytics.

8. The Challenges concerning XR Systems

The integration of Extended Reality (XR) in biomedical applications has been accompanied by various technical challenges that need to be addressed to ensure the efficacy and reliability of these technologies. Computational limitations, tracking issues, and enhancing user interactions are among the foremost concerns. XR experiences can suffer from latency due to limited computational bandwidth, potentially leading to collisions with physical objects when using immersive Head-Mounted Displays (HMDs). Additionally, location-based Augmented Reality (AR) systems might encounter inaccuracies in localization, causing a misalignment between the virtual and physical worlds. To enhance the reliability of XR, efforts are being made to improve these aspects of tracking, computation, and interaction. While XR's potential is promising, there are significant privacy, security, and ethical considerations to be addressed as these technologies gain popularity. Privacy breaches could occur through unauthorized access to cameras and GPS in mobile AR applications, posing risks to user data and experiences. The complexities of input sensors, including microphones and GPS, raise concerns about potential security vulnerabilities. In collaborative XR environments, intellectual property theft and identity manipulation are areas of vulnerability that demand attention. Mixed Reality (MR) systems present their own set of challenges. Achieving seamless integration of image capture components, computer vision, tracking, image fusion, and display is crucial but complex. The computational complexity and latency within each component must be managed to ensure real-time performance, particularly in medical applications. The Field of View (FOV) in MR glasses is also a consideration, as a narrow FOV can limit the usability of these systems. Memory storage and energy consumption present bottlenecks for mobile MR devices that require real-time 3D graphics rendering. In the realm of Virtual Reality (VR), several challenges persist. Hardware modifications and updates often lead to content compatibility issues, hindering the consistent quality of VR experiences.

Developing high-quality VR content is resource-intensive and time-consuming, while the user experience hinges on well-designed hardware. However, VR devices can also induce negative side effects such as motion sickness, eye fatigue, and nausea. Furthermore, there's growing concern about the potential for VR addiction, especially among teenagers, due to its immersive and isolating nature. This phenomenon can negatively impact physical and psychological well-being.

In educational contexts, the adoption of VR and AR also faces obstacles. Lack of focused attention, limited time to master the technology, high implementation costs, and infrastructural challenges like stable internet connectivity can hinder the effective integration of these technologies in classrooms. Virtual environments may demand spatial navigation skills and technological literacy, which can be particularly challenging for younger students. Despite these challenges, VR and AR are gaining popularity in educational settings. Addressing these technical, privacy, security, and ethical challenges is crucial for the continued development and successful implementation of XR technologies across biomedical applications. It requires a concerted effort from researchers, developers, and policymakers to ensure that these technologies provide safe, effective, and ethically sound solutions for healthcare, education, and beyond.

9. AI Revolution within Healthcare Systems

Artificial intelligence (AI) encompasses a variety of technologies, each with its own relevance to the healthcare sector. These technologies support different processes and tasks, offering a wide range of applications. Machine learning, including neural networks and deep learning, is a prevalent form of AI. It involves training models with data to make predictions and decisions. In healthcare, machine learning finds application in precision medicine, predicting treatment success based on patient attributes and contexts. Neural networks and deep learning are more complex forms of machine learning, used for tasks like disease prediction and radiology image analysis. Natural language processing (NLP) is another AI field, focusing on understanding human language. It involves statistical and semantic approaches, aiding tasks such as clinical documentation analysis and transcription. Rule-based expert systems, while used for clinical decision support, are being replaced by data-driven approaches like machine learning. Physical robots, increasingly collaborative and intelligent, are applied in various settings, including surgical procedures. Robotic process automation (RPA) involves structured digital tasks for administrative purposes, enhancing efficiency in areas like claims processing and billing. AI's implications for diagnosis and treatment are substantial. Early AI systems were rule-based, but recent developments in machine learning, deep learning and big data have led to probabilistic and evidence-based diagnosis and treatment predictions [37]. AI technology providers like Google and startups are focusing on AI-driven diagnosis and treatment applications, while genomic-based precision medicine is gaining traction [38]. However, the integration of AI with clinical workflows and electronic health record (EHR) systems remains a challenge [39]. Patient engagement and adherence benefit from AI, personalizing and contextualizing care. Machine learning and business rules are used to provide nuanced interventions, enhancing patient participation [41,42]. Administrative applications of AI include robotic process automation for claims processing, chatbots for interaction, and machine learning for claims and payment administration.

10. Results and Findings

The rapid expansion of AI applications has brought about a pressing need for comprehensive guidelines and ethical frameworks to govern its multifaceted uses across research, clinical practice, and public health. While existing regulations might not cover the full spectrum of AI applications, relying solely on established regulatory mechanisms may fall short of ensuring public trust and accountability. To address all these challenges, a systemic oversight approach known as AFIRRM (Assessment, Foresight, Innovation, Regulation, Responsibility, and Monitoring) has been proposed as a governance blueprint for a probable solution. In the realm of AI-driven research, this entails incorporating reflexive assessments by ethical review committees that evaluate both scientific and societal implications, potentially involving new professional figures like social scientists. Research funders could require monitoring mechanisms as part of the research plans and establish multidisciplinary committees for periodic assessment.

For large-scale AI-driven projects involving community data, inclusive practices must be experimented with to ensure broad social learning across various epistemic communities. In the context of patient care, clinical validation is critical. While tailored evidence standards are essential for responsible clinical innovation, they alone cannot address the spectrum of ethical issues arising. Hospitals might establish ***"clinical AI oversight bodies"*** to advise on technology adoption, monitor its impact on patient journeys, and ensure engagement throughout care processes. As AI-driven diagnostics become prevalent, consent requirements need to adapt to highly automated data processing. In public health, AI's enhanced granularity in disease surveillance and health promotion necessitates community-level negotiations to avoid disempowerment and maintain public trust. Community-wide inclusive deliberations will be pivotal in defining acceptable data collection and algorithmic analysis boundaries.

These initiatives exemplify steps toward establishing AI as a socially robust technology. While uncertainties surround this transformative journey, societal stakeholders, including scientific and clinical institutions, are encouraged to experiment with governance frameworks that harness AI's benefits for knowledge and health while addressing emerging ethical challenges. In parallel, the narrative shifts to XR (Extended Reality) technology, which, despite its existence for decades, has recently gained widespread attention. XR applications, particularly in biomedical engineering, are on the rise. This research explored current trends in XR within medicine and biology. XR, especially VR, facilitates the visualization and analysis of 3D models across various scales, from molecular structures to anatomical representations. Integrating XR tools in education enhances learning, as seen in teaching cell structures and anatomy at educational levels. XR also finds application in telehealth, therapy, and surgical planning, enabling remote consultations and treatments. While XR's potential is evident, challenges in software, hardware, user experience, affordability, and mitigating side effects must be addressed before it can be widely embraced. The research also tackles the ongoing progress and potential of XR technology in biomedicine, acknowledging hurdles that require resolution to realize its full potential for public use. To understand the impact of AI in healthcare with opportunities, directions Figs. 5 and 6 illustrates the visual overview concerning the matters.

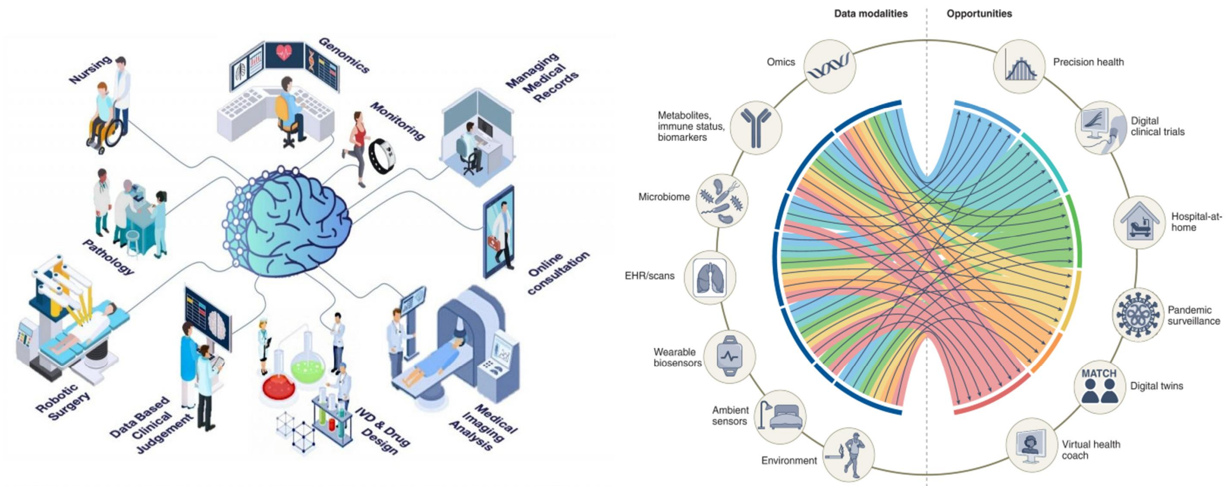

Fig. 5. A Visual Representation of the research findings 1.

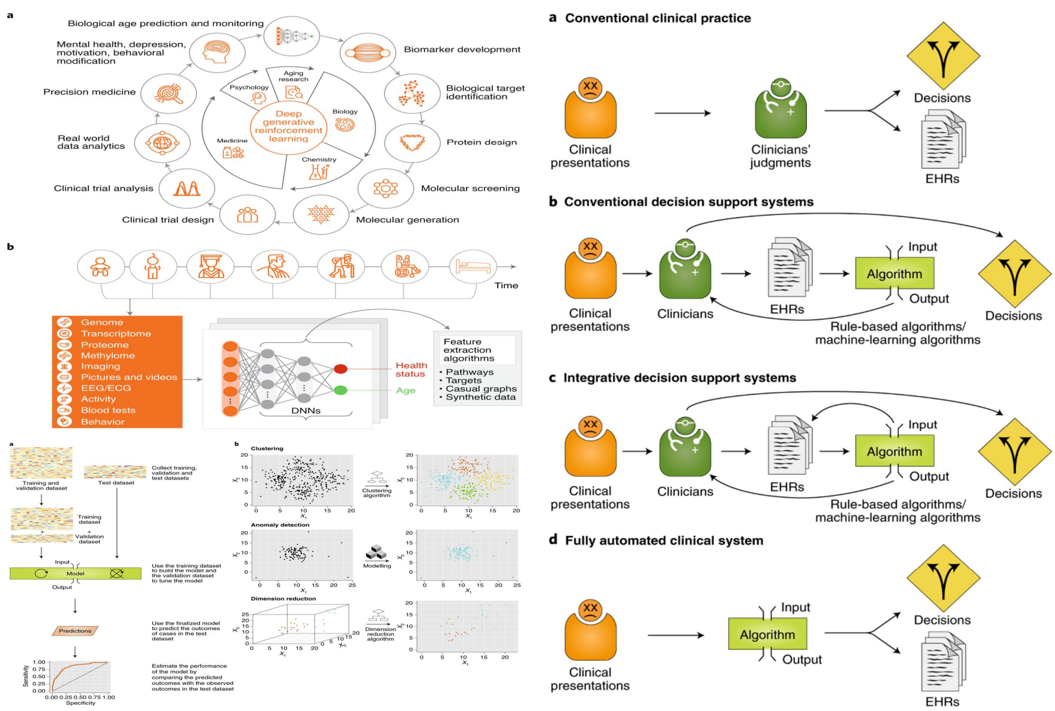

Fig. 6. A Visual Representation of the research findings 2.

11. Discussions and Future Directions

AI is set to play a significant role in the future of healthcare, particularly through machine and deep learning, which is driving the advancement of precision medicine. Despite initial challenges in diagnosis and treatment recommendations, AI is expected to excel in these areas as well. The rapid progress in AI for imaging analysis suggests that, machine examination of radiology and pathology images will become common. Existing applications of speech and text recognition for tasks like patient communication and clinical note capture will expand. The main hurdle for AI's adoption in healthcare lies in its integration into daily clinical practice. Regulatory approval, EHR system compatibility, standardization, clinician training, funding, and ongoing updates pose challenges that will take time to address.

12. Conclusions

While AI is unlikely to replace human clinicians on a large scale, it will enhance their efforts, enabling them to focus on human-centric skills while working alongside AI technologies. In the next few years, limited AI use in clinical practice is expected, with more extensive integration within a decade. The popularity of XR technology, despite its long history, has surged in recent years, particularly in the field of biomedical engineering. Despite challenges, XR applications are being developed across medicine and biology. The research also highlights current trends in XR implementation within these respective domains. XR, particularly VR, is utilized to visualize and analyze 3D models, spanning molecular to anatomical scales. Its integration in education enhances learning, with XR being adopted to teach biological concepts from high school to university levels. The technology shows promise in replacing traditional cadaver-based training for medical students and is entering telehealth and therapy, aiding remote consultations and treatments. The Case studies illustrate XR's potential, including learning with Google Cardboard, visualizing single-cell protein images, and surgical planning using AR and VR. While XR's use in biomedicine is growing, challenges in software, hardware, user experience, and affordability must be addressed for widespread daily use.

Supplementary information

The various original data sources some of which are not all publicly available, because they contain private information. The available platform provided data sources that support the findings and information of the research investigations are referenced where appropriate.

Conflict of Interest

There are no Conflict of Interest or any type of Competing Interests for this research.

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