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Beatrice Aruanno
Department of Civil and Industrial Engineering,
University of Pisa,
Largo Lucio Lazzarino 2,
56122 Pisa, Italy
e-mail: beatrice.aruanno@unipi.it

Monica Bordegoni
Department of Mechanical Engineering,
Politecnico di Milano,
Via La Masa 1,
20156 Milano, Italy
e-mail: monica.bordegoni@polimi.it

Marina Carulli
Department of Mechanical Engineering,
Politecnico di Milano,
Via La Masa 1,
20156 Milano, Italy
e-mail: marina.carulli@polimi.it

Giorgio Colombo
Department of Mechanical Engineering,
Politecnico di Milano,
Via La Masa 1,
20156 Milano, Italy
e-mail: giorgio.colombo@polimi.it

Marco Rossoni
Department of Mechanical Engineering,
Politecnico di Milano,
Via La Masa 1,
20156 Milano, Italy
e-mail: marco.rossoni@polimi.it

Tsz Ho Kwok
Department of Mechanical, Industrial and Aerospace Engineering,
Concordia University,
Montreal, QC H3G 1M8, Canada
e-mail: tszho.kwok@concordia.ca

Theodore Lim
Institute of Mechanical, Process and Energy Engineering,
Heriot-Watt University,
Riccarton, Edinburgh EH12 6JT Scotland, UK
e-mail: t.lim@hw.ac.uk

Extended Reality in Industry and Healthcare: Current Trends and Future Perspectives

Extended reality (XR) technologies are no longer peripheral innovations but emerging cornerstones of human–technology interaction across critical sectors. This article takes the position that engineering and healthcare represent the most mature and strategically relevant domains for XR adoption, given their safety-critical nature, intensive training requirements, and strong alignment with the human-centric visions of Industry 5.0 and Healthcare 5.0. We synthesize evidence from product design, manufacturing, training, and patient care to demonstrate how XR is reshaping workflows, skills, and therapeutic practices. Beyond surveying applications, we argue that the future of XR depends on its integration with artificial intelligence, digital twins, and multisensory feedback, converging into systems capable of perceiving, reasoning, and adapting to complex physical and human environments. We contend that widespread adoption will remain limited without open standards, validated protocols, and robust evaluation frameworks addressing safety, interoperability, and data governance. By framing XR as both a technological enabler and a societal imperative, this position article calls for coordinated action among researchers, practitioners, and policymakers to realize XR's role in building sustainable, personalized, and participatory innovation ecosystems.
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Keywords: extended reality, immersive technology, human-centered innovation, digital industry, XR in manufacturing, XR for training, XR in healthcare, human–computer interfaces/interactions, virtual and augmented reality environments, virtual prototyping

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[1] Corresponding author

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Hugo I. Medellin-Castillo
Department of Mechanical and Electrical Engineering,
Universidad Autonoma de San Luis Potosi,
San Luis Potosi 78290, Mexico
e-mail: hugoivanmc@uaslp.mx

Karthik Ramani
Department of Mechanical Engineering,
Purdue University,
West Lafayette, IN 47907
e-mail: ramani@purdue.edu

Daniele Regazzoni
Department of Management, Information and Production Engineering,
University of Bergamo,
Via Pasubio,
24044 Dalmine BG, Italy
e-mail: daniele.regazzoni@unibg.it

Caterina Rizzi[1]
Department of Management, Information and Production Engineering,
University of Bergamo,
Via Pasubio,
24044 Dalmine BG, Italy
e-mail: caterina.rizzi@unibg.it

Andrea Vitali
Department of Management, Information and Production Engineering,
University of Bergamo,
Via Pasubio,
24044 Dalmine BG, Italy
e-mail: andrea.vitali1@unibg.it

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1 Introduction

Extended reality (XR) encompasses a spectrum of technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), and more recent multisensory variants that merge real and virtual environments to create interactive and immersive experiences [1]. XR immerses users in virtual or augmented environments that feel realistic, making tasks and experiences more engaging and effective. Once primarily associated with entertainment and gaming, XR has evolved into a transformative tool across domains where spatial cognition, training, and decision-making are critical. With rapid advances in hardware, software, and sensory feedback, XR is now emerging as a strategic enabler in safety-critical, data-intensive, and human-centered domains.

Unfortunately, technology developers often promote their innovations without adequately aligning them with the specific needs, readiness, or strategic goals of potential users. The disconnect between the potential of XR and how it is being used can lead to inefficiencies and hesitation to invest further in XR innovations and applications. The adoption of these technologies remains indeed challenging. Major obstacles include the lack of standardized approaches, knowledge gaps, and a shortage of skilled workers. In addition, uncertainties about the benefits, costs, and how to effectively integrate XR make many industries slow or hesitant to adopt XR [2].

Despite these challenges, the potential of XR to transform industries and enhance business models is undeniable. As XR continues to evolve, it offers a broad range of applications that can create significant opportunities for innovation and growth across multiple sectors. Experiences from specific use cases demonstrate rising interest, particularly when applications provide tangible benefits and motivate investment in research and development.

This article takes the position that engineering and healthcare represent the most mature and societally relevant domains for XR adoption and, therefore, provide the strongest lens through which to assess both current impact and future potential. These fields share critical characteristics: They involve high-risk environments where errors are costly, rely heavily on training and simulation, and require negotiation between human performance and complex technical systems, with the human remaining central. Just as importantly, they align directly with broader societal paradigms: *Industry 5.0*, which emphasizes sustainable and human-centric manufacturing [3], and *Healthcare 5.0*, which prioritizes personalized, data-driven, and participatory care [4]. From a research and innovation standpoint, industry [5] and healthcare [6] are among the most extensively studied and invested domains within the XR landscape. According to the XR Association's State of the Industry Report [7], these sectors are leading adopters of immersive technologies, with sustained growth in enterprise deployment and R&D initiatives.

This article examines XR applications in four strategically relevant domains: product design, training, manufacturing, and healthcare. In product design, XR facilitates ideation, prototyping, and collaborative evaluation, allowing stakeholders to visualize and interact with digital models at early stages, thereby reducing reliance on costly physical prototypes. In training, XR supports safe, repeatable, and scalable experiential learning across multiple sectors, including industrial operations and clinical education. For this reason, training is treated as a cross-cutting domain in this

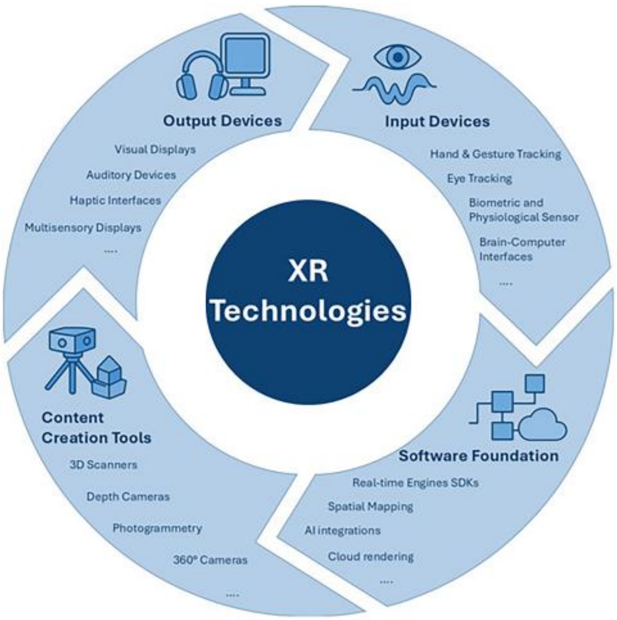

Fig. 1 Outline of extended reality technologies

article, rather than confined within industry- or healthcare-specific discussions. This reflects its methodological commonalities: immersive learning environments, multisensory feedback, and real-time performance analytics are broadly applicable regardless of sectoral boundaries. In manufacturing, XR enhances interaction with digital twins, ergonomics, and human–robot collaboration, enabling operators and engineers to test, validate, and optimize complex systems before real-world deployment [8]. In healthcare, XR is increasingly used not only for professional training but also for patient-centered applications, including rehabilitation, therapy, and remote treatment, opening new perspectives for personalized and participatory care models.

By structuring the discussion around these four domains, this article highlights both the shared enablers of XR adoption [e.g., multisensory immersion, artificial intelligence (AI) integration, digital twins] and the domain-specific challenges that continue to shape XR's trajectory. The decision to merge training into a dedicated section underscores its role as a transversal function, bridging industry and healthcare and pointing to the broader societal importance of workforce upskilling and knowledge transfer in the era of XR.

The remainder of this article is organized as follows. Section 2 reviews the state of XR technologies, outlining the current hardware and software landscape that underpins immersive applications. Section 3 examines XR in product design, with emphasis on how immersive tools reshape ideation, prototyping, and collaborative evaluation. Section 4 presents XR for training as a cross-cutting domain, illustrating its role in workforce development across both industrial and healthcare contexts. Section 5 explores XR in manufacturing, focusing on ergonomics, digital twins, and human–robot collaboration. Section 6 discusses XR in healthcare, highlighting patient-centered applications such as rehabilitation, therapy, and remote care. Finally, Sec. 7 addresses challenges and future directions, including multisensory XR, AI integration, spatial intelligence, and policy initiatives that will shape the next generation of human-centered XR systems.

2 Extended Reality Technologies

XR technologies combine hardware and software to merge physical and virtual spaces. In recent years, advances in displays, input systems, and auxiliary content creation tools have made XR increasingly viable beyond entertainment; however, significant bottlenecks still limit its large-scale adoption in industry and healthcare. Recent progress has driven XR hardware toward high-fidelity multimodal output devices that stimulate human senses during immersive experiences, together with diverse input technologies that capture user actions and adapt systems in real time. In parallel, auxiliary devices play a crucial role in creating XR content, while software advancements are fundamental for developing engaging virtual environments (Fig. 1).

This section reviews the technological foundations of XR, while positioning them within the broader requirements for human-centered, safety-critical ecosystems.

2.1 Extended Reality Output Devices. Output devices are central to XR environments. Vision is the primary targeted sense, and display hardware has seen major advances in recent decades [2], including head-mounted displays (HMDs) [9], handheld devices such as smartphones and tablets, and stereoscopic displays like 3D monitors and projectors [10]. Modern HMDs combine high-resolution visuals with a wide field of view, enabled by advances in micro-displays, optics, and graphics. VR headsets now render near-photorealistic virtual environments in real time, while AR headsets (optical or video see-through) overlay digital imagery onto the real world.

Following the principle of multimodality, XR also stimulates other senses to enhance immersion [11]. Auditory displays convey spatial cues and realism [12]; immersive audio has been shown to be critical for presence and interactivity [13]. XR soundscapes can include ambient sounds, directional effects, speech, or music. Most XR headsets integrate audio output, enabling 3D spatial audio that simulates sound from specific locations in the virtual or augmented environment.

Haptic displays provide tactile and force feedback, simulating touch, texture, and force sensations when users interact with virtual objects. Achieving high-fidelity haptics is more challenging than visual or audio output due to the complexity of human touch perception. Current devices range from gloves with force or vibration feedback, to full-body haptic suits, and skin-integrated adhesive patches stimulating mechanoreceptors [11]. Consumer XR haptics remain limited to simple vibrotactile motors in hand controllers, though advanced controllers now add variable resistance or moving surfaces for richer feedback. In addition, mid-air haptic technologies have emerged, based on ultrasonic phased arrays that focus acoustic radiation pressure onto a user's hands to create the sensation of touch in mid-air with no gloves or controllers.

Even though less explored, olfactory displays have rapidly progressed. Studies show that adding smell stimuli to a virtual environment significantly increases users' sense of presence, immersion, and realism [14,15], can affect emotions and memory, and even enhance learning outcomes [16]. Industrial research has also demonstrated olfactory-enhanced environments for simulating product experiences under real-world-like conditions [17]. Recent prototypes include wearable olfactory scent dispensers attached to VR controllers, the user's body, or directly onto headsets near the user's nose. These scent interfaces release small amounts of various odors on demand, often using microfluidic cartridges, atomizers, or fans to blow scented air toward the user's nostrils for precise timing.

Despite displays being the most visible drivers of XR adoption and head-mounted displays now achieving near-photorealistic rendering, visual fidelity alone is insufficient. True immersion requires multimodal output: spatial audio to enhance presence, haptics to replicate touch and resistance, and olfactory cues to anchor experiences in memory and emotion. Although olfactory and gustatory interfaces are still experimental, they illustrate the broader trajectory: XR is moving toward full-body, multisensory experiences. Without this progression, XR will remain a niche visualization tool rather than a platform for embodied interaction in Industry 5.0 and Healthcare 5.0.

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2.2 Extended Reality Input Devices. XR applications rely on diverse technologies to capture user interactions and measurements [18]. Interaction devices include handheld controllers, hand and motion-tracking systems, and eye tracking.

Hand controllers remain the most common consumer input. Simple and reliable since early VR, they let users point, select, and manipulate objects with low latency. Typically wireless, they combine inertial sensors with optical tracking (external or inside-out) to capture 3D hand position and orientation. Equipped with buttons, triggers, and joysticks, they also provide basic haptic feedback via vibration motors. Recent designs integrate capacitive and force sensors to detect finger presence and grip strength [19].

To enable more natural input, controller-free hand tracking uses cameras or depth sensors on HMDs to recognize hand position and gestures. Combined with AI, these systems can interpret complex gestures or track full-body motion for avatars. Alternatively, data gloves with bend or magnetic sensors capture finger movements precisely, though they require wearing dedicated hardware.

Eye tracking has gained importance as an input modality, both for active interaction (gaze-based pointing/selection) and passive context sensing, such as inferring user intent or interest. Many HMDs now integrate infrared eye trackers that monitor gaze in real time. Beyond interaction, eye tracking supports rendering optimization via eye-tracked foveated rendering, which dynamically assigns high-resolution rendering to the foveal region while reducing pixel density in the periphery. Early research highlights that combining gaze tracking with conventional input methods improves interaction efficiency and user experience [11].

An emerging field is the integration of brain–computer interfaces (BCIs) that enable direct communication between the user's brain signals and the virtual environment. EEG-based BCIs can provide an additional input channel beyond conventional senses [20]. This can happen in two ways: through active control, where the user intentionally generates brain signal patterns to issue commands, or through passive sensing, where the system monitors brain signals to infer the user's mental state without explicit commands [20].

Finally, XR increasingly incorporates biometric and physiological sensors to monitor users' physical and emotional states. Modern wearables track heart rate, respiration, skin conductivity, and muscle activity, enabling applications in health, fitness, and biofeedback. The comprehensive review by Halbig and Latoschik [19] concluded that combining VR with biosensors provides robust methods for objectively evaluating and potentially enhancing user experience [19]. Some consumer XR devices already incorporate such features: e.g., the Valve Index controller can indirectly measure heart rate, while some AR glasses estimate breathing rate from chest movements. However, interpreting biosignals in XR remains a significant challenge.

2.3 Auxiliary Devices for Extended Reality Content Creation. XR ecosystems benefit from auxiliary hardware to capture and digitize real-world content, enabling the creation of realistic 3D models, environments, and media for immersive XR experiences.

A key requirement is the acquisition of 3D representations of objects and spaces. Modern RGB-D cameras have transformed content creation, allowing real-time scanning of rooms, objects, and even people. Handheld or tripod-mounted depth cameras, as well as mobile devices with integrated depth sensors (e.g., LiDAR-equipped smartphones and tablets), can generate textured meshes or point clouds for direct use in XR applications [21]. Depth cameras are also widely used for capturing human motion and facial expressions, improving the realism of avatars. Headsets such as Microsoft HoloLens integrate time-of-flight sensors to support environment mapping and markerless AR anchoring [22]. In parallel, photogrammetry has become a powerful tool for high-resolution 3D reconstruction. By processing photographs taken from multiple viewpoints, creators can generate detailed models of objects and environments that complement depth-based scanning [23].

Another important category is 360-deg cameras, which record panoramic imagery and video to serve as immersive XR content. These devices, equipped with multilens or dual-fisheye systems, can now capture 8K footage and support real-time streaming (e.g., over 5G), making them valuable for VR storytelling, tourism, training, and telepresence [24,25].

2.4 Software Foundations of Extended Reality Technologies. The software layer governs the rendering of virtual environments, manages multimodal devices, and integrates external data sources and workflows [26]. In domains like industry and healthcare, XR software must balance performance, scalability, and reliability, while accommodating domain-specific requirements.

At the core of XR applications are real-time rendering engines, or game engines, which generate interactive 3D environments at high frame rates [27]. Presently, the XR software landscape is dominated by Unity[2] and Unreal Engine,[3] which provide integrated support for 3D graphics rendering, physics simulation, animations, and device integration.

In AR and MR, platforms must align digital and physical worlds. This is achieved through simultaneous localization and mapping (SLAM) techniques, enabling real-time tracking of the user's position and surroundings [28]. Software Development Kits (SDKs) like ARKit (Apple) and ARCore (Google) provide SLAM-based functionalities such as plane detection, surface reconstruction, and real-world anchoring [29].

XR software is increasingly combined with AI, supporting gesture and intent recognition, scene understanding, adaptive content, and physiological/behavioral responsiveness [30]. In healthcare, this supports adaptive rehabilitation or training that responds to user performance [4]. In industry, AI enhances XR-guided workflows by optimizing task sequencing or detecting inefficiencies in real time [31].

Web-based XR solutions, built on standards such as WebXR, and frameworks such as BabylonJS, ThreeJS, and A-Frame, are gaining popularity for their accessibility and ease of deployment [32]. Although less capable in terms of visual fidelity and hardware integration, these tools support lightweight, browser-based experiences for telepresence, remote education, and collaborative design [33].

To reduce ecosystem fragmentation, cross-platform standards such as OpenXR provide unified APIs [34]. Toolkits like virtual reality toolkit and mixed reality toolkit further streamline development by offering modular components for interaction design and spatial user interfaces, promoting reusability and rapid prototyping [35].

Emerging frameworks such as WebXR and OpenXR promise interoperability, yet fragmentation still hampers scalability. More critically, XR software must increasingly integrate AI for scene understanding, adaptive content, and behavioral feedback, and cloud/edge computing for scalable rendering. Cloud rendering and edge computing are emerging as key enablers of high-fidelity XR experiences on constrained devices. Services like NVIDIA CloudXR and Azure Remote Rendering decouple rendering from local hardware, enabling computationally demanding tasks such as computer aided design (CAD) model visualization, anatomical exploration, or real-time factory monitoring in resource-limited settings [36].

2.5 Remarks. Taken together, the current XR technology stack is impressive but uneven. Display and tracking systems have reached a level of maturity that allows compelling immersive

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[2] https://unity.com/

[3] https://www.unrealengine.com/

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experiences, yet other modalities, notably haptics, olfaction, and adaptive physiological input, still lag. This imbalance creates a paradox: XR can convincingly render virtual worlds but struggles to support the full spectrum of embodied interaction that industry and healthcare demand. Content creation pipelines further amplify this challenge. While real-time scanning, photogrammetry, and 360-deg capture make it possible to generate assets, the lack of interoperable formats and validated repositories prevents their reuse across platforms or domains. On the software side, fragmentation between proprietary SDKs and emerging standards slows integration into enterprise and clinical workflows, undermining trust and scalability.

For XR to fulfill its envisioned role in Industry 5.0 and Healthcare 5.0, the trajectory must shift from device-centric innovation toward ecosystem-level integration. This means aligning hardware, content, and software through open standards, multisensory fidelity, and modular platforms that can plug into existing industrial and healthcare infrastructures. Only such convergence will enable XR to function as a dependable, safe, and regulatory-compliant technology, one that can move beyond pilot projects to become a core enabler of human-centered manufacturing, personalized rehabilitation, and participatory healthcare.

3 Extended Reality in Product Design

XR is increasingly valuable in product design, from early concept development to postlaunch user testing [9]. It is transforming the product design process across various industries by enabling more immersive, intuitive, and collaborative ways to create and refine products, environments, and experiences [37].

At the beginning of the design process, in the conceptual and preliminary design phases, XR enables the exploration and validation of complex geometries and the refinement of aesthetics in a virtual space [38,39]. This significantly reduces the need for physical prototypes [40]. Using these virtual prototypes, it is possible to test ergonomics, scale, and aesthetics in VR before any physical model is made. These prototypes can be modified and improved during the design process and used for different testing purposes. As an example, automotive designers have used XR to create virtual mockups of vehicle interiors, allowing for real-time feedback and adjustments before committing to costly production.

In the detailed design, design evaluation, and final validation phases, designers can test how a digital product would look and behave in a real environment using AR and evaluate a product's aesthetics, size, and functionality, or use immersive VR experiences to navigate large products (such as cars, trains, or buildings) and evaluate their features. Automotive companies, such as BMW [41], use VR to evaluate visibility, reachability of controls, and overall driver comfort before building physical mockups.

Table 1 XR tools and their roles in the design process

Design process stage	XR method	Purpose
Conceptual design	Immersive 3D sketching	Form exploration, early spatial reasoning
	Virtual brainstorming spaces	Collaborative ideation in VR
Preliminary design	Virtual prototyping	Evaluate shape, proportions, and early UX
	Mixed reality overlays on sketches	Validate concept in context
Detailed design	CAD-to-VR translation for full-scale inspection	Validate dimensions, tolerances, ergonomic aspects
	Simulation of interaction flows	Evaluate touchpoints, feedback, and logic
Design evaluation	VR usability testing (eye/motion tracking)	Measure user behavior, comfort, and accessibility
	AR contextual visualization	See product use in real-world environments
Final validation	Mixed reality for assembly/testing simulations	Manufacturing validation, part fitment
	Multiuser design review and annotation	Stakeholder feedback and approvals

Additionally, XR methods and technologies are increasingly used for User eXperience (UX) simulation, as they allow real-time observation of how users interact with a product or space in a controlled, virtual setting [42]. For instance, eye tracking integrated in VR headsets can be used to analyze user attention and focus areas during interface testing or retail environment walkthroughs [43]. In consumer electronics, companies use XR to simulate unboxing experiences and interface navigation to detect obstacles that interfere with a smooth, intuitive experience before product launch. Moreover, motion-tracking technologies can be employed to monitor users' physical movements, providing further insight into how users interact with the product and helping designers identify potential ergonomic or usability issues.

With AR technologies, users can interact with digital prototypes in real-world contexts, e.g., visualize how a smartwatch or smart glasses will sit on different wrist or face shapes, using parametric avatars that simulate diverse users. In furniture and interior design, AR applications like "IKEA Place" let users place virtual furniture in their real environment using mobile devices, enabling them to assess scale, fit, and style in situ [44]. These experiences offer valuable feedback on product proportions, aesthetics, and usability under real-world lighting and spatial constraints.

XR also facilitates codesign by enabling geographically dispersed stakeholders to collaborate in virtual environments [45]. Participants (engineers, designers, marketers, and clients) can review 3D models in VR simultaneously, provide instant feedback, leave notes and make iterative improvements, accelerating the design process. XR helps nondesigners (like clients or end users) understand and engage with designs more easily than flat drawings or models. When used throughout the design process, XR facilitates multiscale communication in design reviews [46]. This collaborative capability bridges the gap between digital models and physical implementation, laying the foundation for more efficient manufacturing ecosystems [47]. Several attempts have been made to build new collaborative platforms in this direction. In Ref. [48], an innovative application aimed at enhancing collaborative design reviews in architectural and automotive domains through mobile mixed reality is presented. Similarly, in Ref. [49], a VR platform developed for collaborative and immersive review of automotive designs is described, highlighting its benefits in enhancing engagement, spatial comprehension, and design iteration efficiency.

While current XR applications in product design, summarized in Table 1, already demonstrate clear benefits in terms of visualization, prototyping, and collaboration, their true potential lies in the evolution toward multisensory, AI-driven, and adaptive design environments. Future XR systems will not only allow designers to visualize form and function but also to simulate affective responses, emotional engagement, and sensory interactions, thereby integrating modalities such as sound, scent, and haptics into early-stage evaluations. The convergence of XR with generative AI, digital twins, and parametric user models will enable design ecosystems that adapt in real time to diverse user needs, cultural contexts, and sustainability requirements. In this perspective, XR is shifting from a supportive visualization tool toward a comprehensive design intelligence platform, one that can anticipate, cocreate, and personalize products and experiences in alignment with the principles of Industry 5.0.

4 Extended Reality for Training

XR technologies are transforming training across industrial and clinical domains by providing immersive, repeatable, and safe

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Fig. 2 VR environment for human–robot collaboration

environments for experiential learning. We argue that training should be treated as a cross-cutting domain: while manufacturing, healthcare, and defense differ in content, the methodological foundations of XR training, immersion, simulation, multisensory engagement, and data-driven feedback are consistent across all contexts [50]. This makes XR not just an application but a transversal enabler of workforce development in the era of Industry 5.0 and Healthcare 5.0. These immersive technologies enable experiential

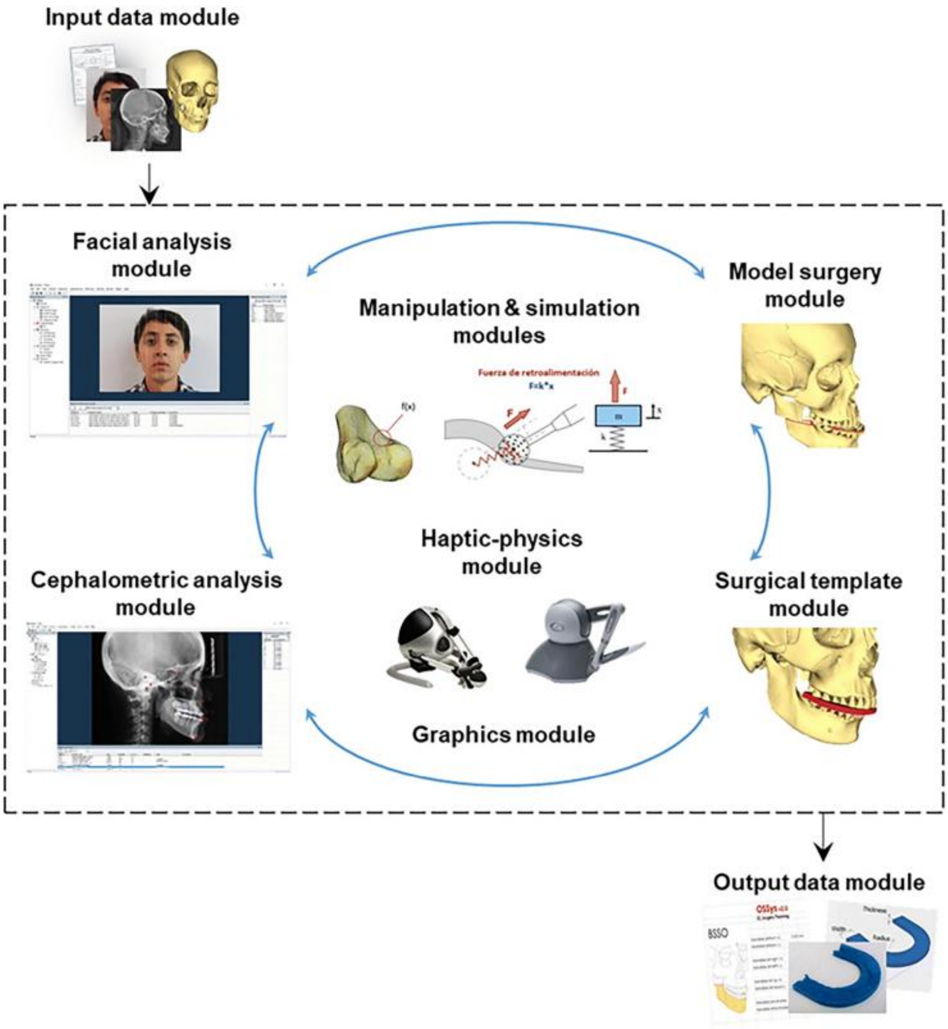

Fig. 3 Architecture of the haptic-enabled OSSys system [55]

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learning in safe, repeatable environments, allowing trainees to gain hands-on experience with complex or hazardous tasks without incurring real-world risk [51].

Recent studies have expanded our understanding of XR's effectiveness in training, highlighting improvements in skill acquisition, long-term retention, procedural accuracy, and transfer to real-world performance. Meta-analyses conducted in 2023 and 2024 have begun to quantify these outcomes across multiple domains, reinforcing XR's position as more than a novelty and confirming its emerging role as an essential tool for workforce development. For instance, a systematic review demonstrated that MR technologies significantly enhance behavioral, cognitive, and affective training outcomes in vocational education and training settings [52].

In manufacturing, XR applications span a wide spectrum, from virtual walkthroughs of assembly lines [53] to highly detailed procedural training, such as computerized numerical control (CNC) machine operation and thermoforming processes [54]. With the widespread adoption of human–robot collaborative workstations, the role of immersive technologies has become even more prominent. The ability to virtually recreate potentially hazardous scenarios is being extensively explored, both from an educational standpoint and to train operators to perform confidently and safely in such environments. Figure 2 shows an example of a VR application used to simulate the interaction between a virtual human and a digital replica of a collaborative robot (cobot).

In the construction industry, XR has been shown to reduce on-site errors and improve safety awareness, with immersive simulations used for equipment handling, hazard identification, and ergonomic training [56]. Healthcare applications continue to lead in complexity and impact, with XR supporting virtual dissection, real-time AR-guided surgery, and neurosurgical training, often combining spatial visualizations with real-world procedures [57]. In defense, XR is used to simulate hazardous missions such as explosive ordnance disposal, offering trainees the opportunity to rehearse decision-making under pressure in fully immersive environments [58].

In the educational domain, recent initiatives have shown that immersive XR laboratories are also highly effective in engineering and materials science training. For example, Aruanno et al. [59] demonstrated that VR-based environments can significantly enhance students" engagement, spatial understanding, and practical skill development in complex technical subjects.

In healthcare, XR has emerged as a powerful enabler for medical training and simulation, offering environments that are safe, repeatable, and adaptable to diverse learning needs [60,61]. Virtual environments allow practitioners to rehearse complex procedures, refine decision-making, and gain confidence without putting patients at risk. Compared to traditional methods like Moodle or Blackboard [62], XR can provide customizable levels of difficulty, real-time feedback, and collaborative interaction, which makes it particularly effective for clinical education [63]. Its effectiveness depends on design principles such as presence, agency, and multisensory engagement, which directly influence the transfer of skills from simulation to real practice [64]. Multisensory feedback, visual, auditory, and haptic, further enhances realism, helping practitioners internalize procedural knowledge more effectively.

Despite clear benefits, adoption is slowed by barriers including the need for specialized hardware, integration with learning management systems, and limited faculty expertise in developing and running XR scenarios. Open standards such as OpenXR and WebXR offer a path to overcome this fragmentation, enabling interoperability across devices and supporting scalable deployment in teaching hospitals and universities [62]. The ability to embed XR directly into existing educational ecosystems is essential if the technology is to move from isolated pilots to mainstream curricula.

Furthermore, a user-centered design approach is essential to ensure usability, adaptability, and engagement in XR medical environments [65]. Two core concepts in this context are *agency*, the user's ability to control actions and make decisions within the virtual environment, and *presence*, the sense of immersion or "being there" in the virtual setting [64]. These two dimensions are closely linked: presence enhances immersion, while agency governs the depth of interactivity. Together, they shape cognitive and motor responses, which are critical for transferring skills learned in XR to real-world clinical contexts. In this sense, auditory feedback can complement or reduce visual overload. Studies show that sound is often processed more quickly than visual stimuli, making it valuable in fast-paced settings like anesthesia monitoring or image-guided surgery. Haptic technologies provide tactile and kinesthetic feedback, simulating sensations such as tissue resistance or tool pressure. These enrich realism, improve manual skill development, and enhance user confidence. Fleury et al. [66] and Samur et al. [67] offer a taxonomic overview of the classes and modes of haptic interfaces and interaction tasks.

A notable example is orthognathic surgery [55,68], one of the most complex procedures in oral and maxillofacial practice. As shown in Fig. 3, traditional training requires years of exposure, but haptic-enabled XR platforms now allow surgeons to rehearse key stages such as cephalometric analysis, model surgery, and occlusion adjustment in a highly realistic virtual environment. These systems combine visual fidelity with tactile feedback, enabling trainees to practice delicate manipulations while reducing patient risk. Evaluation studies demonstrate that such platforms accelerate skill acquisition, improve accuracy, and increase surgeon confidence while also serving as valuable tools for preoperative planning. This case illustrates how XR can bridge the gap between education and practice, positioning it not only as a pedagogical tool but also as an element of the clinical workflow itself.

XR training in healthcare should be considered a strategic infrastructure for developing the next generation of medical professionals. As healthcare systems move toward digital, personalized, and collaborative models, XR has the potential to embed simulation and rehearsal as standard practice, ensuring that skill development keeps pace with technological and clinical innovation.

4.1 Emerging Areas in Training. The next stage of XR training will be defined by the convergence of multisensory technologies, artificial intelligence, and data-driven adaptivity. Multisensory XR, engaging not only vision but also auditory, haptic, and olfactory channels, is already demonstrating its capacity to deepen immersion and accelerate learning [37]. Projects such as Med1stMR [69] show that when XR training environments are enriched with scents and tactile stimuli, participants display higher realism, stronger stress responses, and better knowledge retention. Beyond enhanced realism, this sensory richness builds learner confidence, reduces anxiety, and allows safe exposure to high-stakes scenarios that would otherwise be too risky to replicate.

Simultaneously, integration with wearable sensors and eye-tracking technologies is enabling real-time analysis of cognitive load, emotional stress, and focus [70]. This data-driven feedback loop allows systems to adjust the training content on the fly, slowing down, repeating, or advancing tasks based on physiological and behavioral indicators. In sectors like surgery or aviation, where attention to detail is critical, these features improve not only performance but safety and confidence.

Generative AI is emerging as a second pillar of transformation. By dynamically creating training scenarios, generating voice-guided feedback, and adapting to learner errors in real time, AI systems enable highly personalized and scalable training. When combined with wearable sensors and eye tracking, XR platforms can monitor stress levels, cognitive load, and attentional focus, creating a closed feedback loop that continuously adapts training content to the learner's physiological and behavioral state [71].

A third dimension of innovation is the integration of digital twins. Rather than training in static simulations, learners increasingly interact with living representations of operational systems that evolve in real time. This development links XR training directly to the infrastructures of Industry 5.0 and Healthcare 5.0,

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where digital twins are expected to serve as the backbone of human–machine collaboration and personalized care.

These developments signal a transition from XR as a tool for static rehearsal to XR as an intelligent, adaptive ecosystem for lifelong learning. We contend that multisensory realism, AI-driven adaptivity, and digital-twin integration are not optional enhancements but strategic imperatives if XR training is to become mainstream in safety-critical and knowledge-intensive domains. They represent the foundation of a new paradigm where XR evolves from providing immersion to delivering true spatial intelligence for education and workforce development. Looking ahead, XR training is evolving through tighter integration with digital twins, allowing trainees to interact with real-time representations of operational systems [72]. We can also expect growth in adaptive XR learning platforms, which tailor entire curricula to individual user profiles. As hybrid work and remote collaboration become standard, XR is likely to play a central role in enabling hands-on education [73] and active learning [74]. XR is becoming a suitable technology for modern training strategies [75]. By merging immersion, interactivity, intelligent feedback, and multisensory engagement, XR equips learners not only to perform tasks, but to understand, refine, and master them in ways traditional training cannot match.

Despite the progress, challenges remain. Technical barriers such as the need for high-fidelity tracking, content customization, and specialized development expertise can limit broader adoption. Additionally, more research is needed to validate the long-term effectiveness of XR training and to define best practices for deployment across diverse learning contexts. Nonetheless, XR continues to expand its role in industry training, offering a powerful and flexible platform to meet the evolving demands of modern workforce education.

5 Extended Reality in Manufacturing

Recently, XR has served as a key enabler of digital-twin technologies, enabling operators to interact with virtual replicas of production systems, facilitating training on new processes, maintenance planning, and workflow optimization, thereby minimizing downtime and operational errors [76]. The fusion of XR with real-time internet of things (IoT) data enhances decision-making by providing augmented views of production lines, allowing for dynamic identification of bottlenecks and potential safety hazards [77]. For example, leading aerospace manufacturers have implemented XR-based maintenance simulations to reduce training times and improve safety outcomes [78]. Conducting these tests in a virtual environment involving human interaction before deploying the solution in the field offers clear advantages.

In this sense, XR has emerged as a key enabler of human-centric interaction within the Industry 4.0 framework, facilitating real-time engagement with cyber–physical systems and improving situational awareness on the shop floor [3]. This role aligns with the human-centered principles emphasized by the evolving Industry 5.0 paradigm, in which XR contributes to the transition from traditional cyber-physical systems to human–cyber–physical systems by integrating contextual data, computational intelligence, and real-world sensory cues to support intuitive human interaction [79]. In this context, several research works focus on using XR as a "test-before-invest" tool. For example, XR platforms are being specifically designed to support the evaluation of dynamic path planning strategies for human–robot collaboration in manufacturing, allowing for real-time collision avoidance and path replanning [80].

Beyond applications in which VR is employed as a standalone tool, a growing body of research is focused on promoting the industrial adoption of XR technologies through increased automation and the integration of advanced communication infrastructures [81]. In this context, automation refers to the capability of an XR application to dynamically respond to changes originating from external data sources. This research direction stems from the premise that broader industrial uptake of XR will be feasible only if the development and maintenance of XR applications do not require substantial human resources, particularly in companies whose core business lies outside software development. This perspective is increasingly reflected in the literature [82], particularly under the umbrella of "virtual commissioning," which highlights use cases where VR systems are automatically configured and updated so as to mirror evolving physical or digital production environments (Fig. 4).

In relation to the capabilities enabled by next-generation communication infrastructures, e.g., 5G and emerging 6G networks, recent research has leveraged the low latency and high bandwidth of these technologies to offload computationally intensive tasks, such as real-time rendering and physics simulation, to the cloud [83]. This architectural shift allows end-user devices, such as HMDs, to function primarily as thin clients focused solely on visualization and user interaction. Furthermore, the adoption of web-based platforms and technologies has facilitated the development of collaborative and distributed XR workspaces, often framed within the broader concept of the metaverse. This trend is reinforced by the growing use of frameworks based on WebXR (e.g., Babylon.js), which offer lightweight, modular, and scalable alternatives to traditional monolithic rendering engines.

5.1 Industrial Ergonomics. In the context of modern manufacturing, the adoption of immersive technologies such as XR is profoundly reshaping processes, roles, and operational

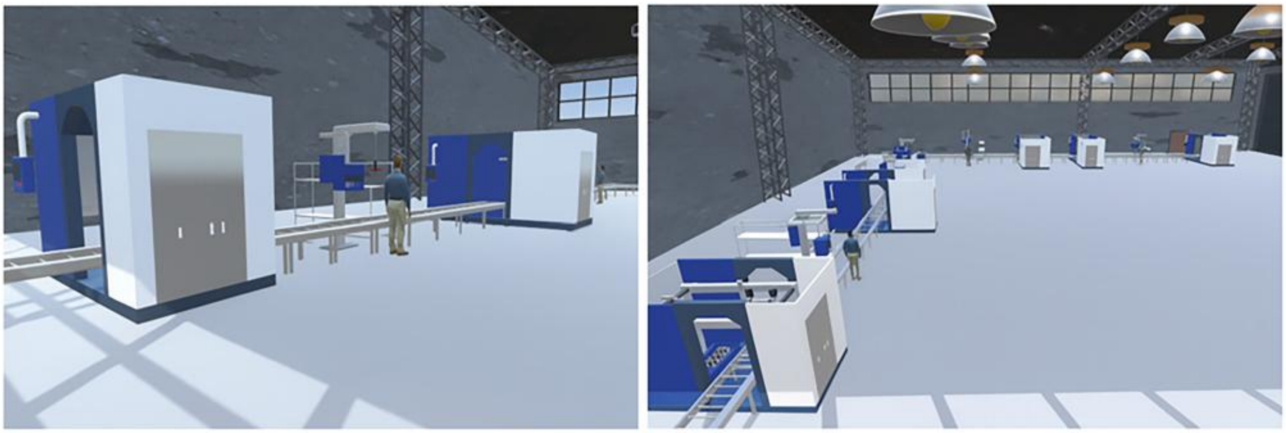

Fig. 4 VR walkthrough of an assembly line. Reprinted from Ref. [82].

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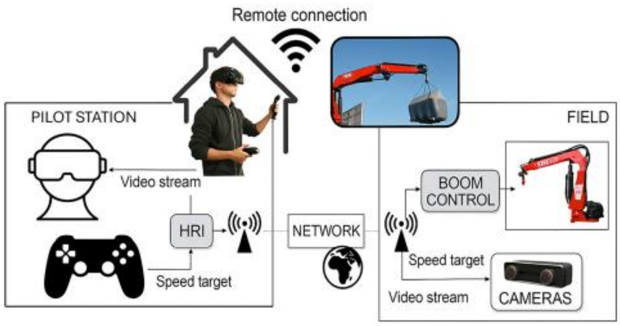

Fig. 5 Framework for remote control and monitoring of cranebot via VR interface [87]

environments. Among the areas most impacted by this transformation, industrial ergonomics stands out as one of the most significant developments in recent years. The integration of XR with ergonomic principles not only enhances human–machine interaction but also enables the design of safer, more adaptive, and cognitively sustainable workspaces, integrating numerous innovations previously discussed and laying the basis for a new generation of ergonomic systems focused on human well-being.

The increasing emphasis on workers' well-being in intelligent manufacturing is driving the development of innovative solutions to monitor and enhance human performance in the workplace. Central to this evolution is the integration of advanced technologies, including AI, XR, and the IoT, into ergonomic systems that move beyond traditional, observation-based approaches [3]. This highlights a broader transformation in ergonomics, from conventional approaches to advanced and intelligent systems that continuously monitor health, safety, and productivity.

Within this evolving framework, physical ergonomics plays a fundamental role. It focuses on designing workplaces, tools, and tasks that fit the human body's capabilities and limitations, aiming to reduce strain, fatigue, and the risk of musculoskeletal disorders [84–86]. In industrial settings, one of the most promising applications of physical ergonomics is the integration of cobots, which are designed to work alongside human operators, sharing tasks in a safe and adaptive [87]. By taking over repetitive, heavy, or awkward movements, cobots help minimize physical stress on workers.

This is particularly evident in industrial operations such as those on construction sites, where human operators are frequently exposed to high-risk conditions, especially when managing heavy equipment or performing demanding manual activities such as operating heavy machinery including cranes, excavators, and bulldozers. Traditionally, crane operation requires highly skilled operators who must manage the complexities of nonlinear hydraulic actuation under harsh outdoor conditions. These demands have contributed to a growing shortage of qualified workers across the construction sector. The study by Duz et al. [87] presents an innovative approach to assessing cognitive ergonomics by transforming traditional cranes into remotely operated robotic systems (cranebot), enhancing safety, simplifying operation, and making them accessible even to untrained users. The framework developed is illustrated in Fig. 5.

In their study, a cranebot is designed to control crane movements during operations, built upon intuitive user control and remote operator accessibility. Moreover, instead of conventional manual control of each hydraulic joint, operators manage the boom tip directly via a Cartesian control interface. This removes much of the cognitive burden associated with operating a complex, multidegree-of-freedom system. The authors employed the NASA Task Load Index for assessing perceived workloads, obtaining a score of 33.33%, a relatively low workload comparable to daily activities like casual conversation or light computer work. This suggests that the proposed approach can significantly reduce the cognitive and physical burden associated with crane operation.

Therefore, XR technology is playing a transformative role, enhancing both productivity and operator well-being, supporting a more sustainable and human-centered approach to manufacturing in line with the principles of Industry 5.0 [88]. XR improves both the ergonomic quality of industrial tasks for operators and the analytical capabilities of ergonomists. In fact, traditional assessment indexes (e.g., RULA, REBA, and OWAS) are widely used but limited by subjectivity, static evaluation, and low temporal resolution [89].

The design of XR solutions for ergonomics is based on a foundation of engineering knowledge and methodological approaches, particularly from the field of digital human modeling. The human digital twin becomes the central asset in the ergonomic analysis pipeline, capable not only of reflecting human motion and workload but also of predicting risks to worker health and safety using advanced AI techniques. Figure 6 depicts the main

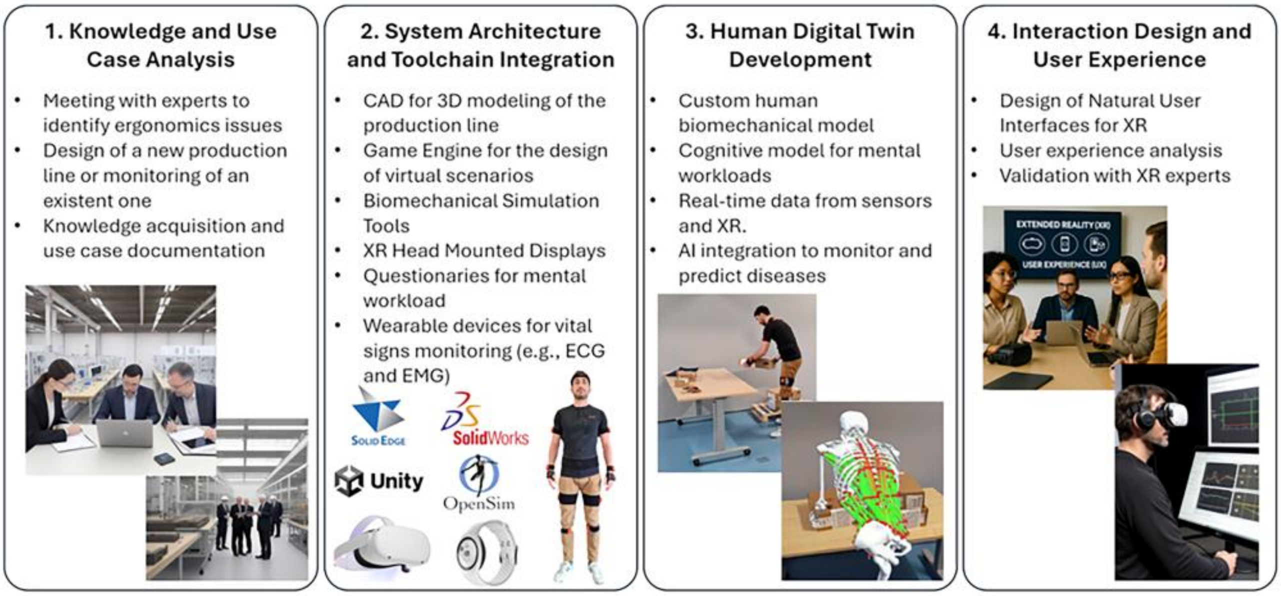

Fig. 6 Main steps to design an XR application to assess ergonomics in industry

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steps to design and develop an XR application for ergonomics purposes, highlighting the role of hardware, software, data flow, and analytical engines.

Therefore, XR-based ergonomic tools are evolving into advanced platforms that combine real-time data collection using motion capture systems and wearables to continuously track operator movements and postures, with immersive visualization that presents ergonomic data in context through AR or VR to support immediate and intuitive insights. They also enable interactive simulations that allow early-stage ergonomic testing in virtual environments, reducing reliance on physical prototypes. Moreover, these platforms promote a shift from reactive to proactive methodologies, making it possible to design custom human digital twins of workers that integrate motion capture systems, electromyography sensors, physiological monitors, and AI analytics [79,90–92].

XR supports both the design of future production lines and the assessment of existing ones. On the one hand, VR for Design enables interaction with digital twins of future workstations, helping ergonomists to identify and correct design flaws before implementation [93]. On the other hand, AR for Monitoring provides real-time ergonomic insights in actual work environments, allowing for unobtrusive data collection and evaluation [1].

Numerous tools can be combined to create a complete IT framework for ergonomics assessment: motion capture systems, wearable devices, and physiological monitors allow enhanced real-time assessment of stress and workload. An example of this approach can be found in the AR4Ergo platform [94], designed as an AR tool that supports ergonomists by delivering real-time calculations of standard physical ergonomics indexes and simulating musculoskeletal loads through biomechanical virtual models.

XR can further enrich this framework by enabling immersive simulations of work environments, allowing for controlled evaluations of interface design, task complexity, and operators' responses. Combining these technologies with AI for multimodal data analysis promotes a wide understanding of operator health and task performance. This integrated framework not only advances traditional ergonomic assessments but also fosters innovation in designing safer and more efficient workplaces through collaborative robotics and immersive technologies.

6 Extended Reality in Healthcare

XR has the potential to significantly improve patient care in a variety of healthcare domains, particularly in rehabilitation [65,95], therapy [96], patient participation, and remote healthcare [97]. By creating interactive and immersive environments, XR supports personalized and participatory models of care that go beyond traditional treatment settings. Patients can engage in tailored rehabilitation programs, experience reduced pain and anxiety through distraction therapies, or access telemedicine services enriched by immersive visualization. At the same time, the integration of XR with digital twins, wearable sensors, and affective computing opens pathways toward adaptive, data-driven treatment plans that evolve with patient needs. These developments place XR at the heart of the Healthcare 5.0 paradigm, where prevention, personalization, and patient empowerment define the future of medical practice [4].

Besides all the implications discussed in Sec. 4 on training and simulation, the focus here is on patient-centered applications, with particular attention to rehabilitation and therapy, illustrating both current impact and long-term potential.

6.1 Extended Reality and Patients' Rehabilitation. Healthcare rehabilitation practices can benefit from an XR-based approach in a variety of patient conditions. Depending on the functions to restore or compensate, the interaction with a digital immersive environment can improve and speed up the recovery process, while providing patients with a gratifying experience. XR has already shown its valuable potential in facing key rehabilitation

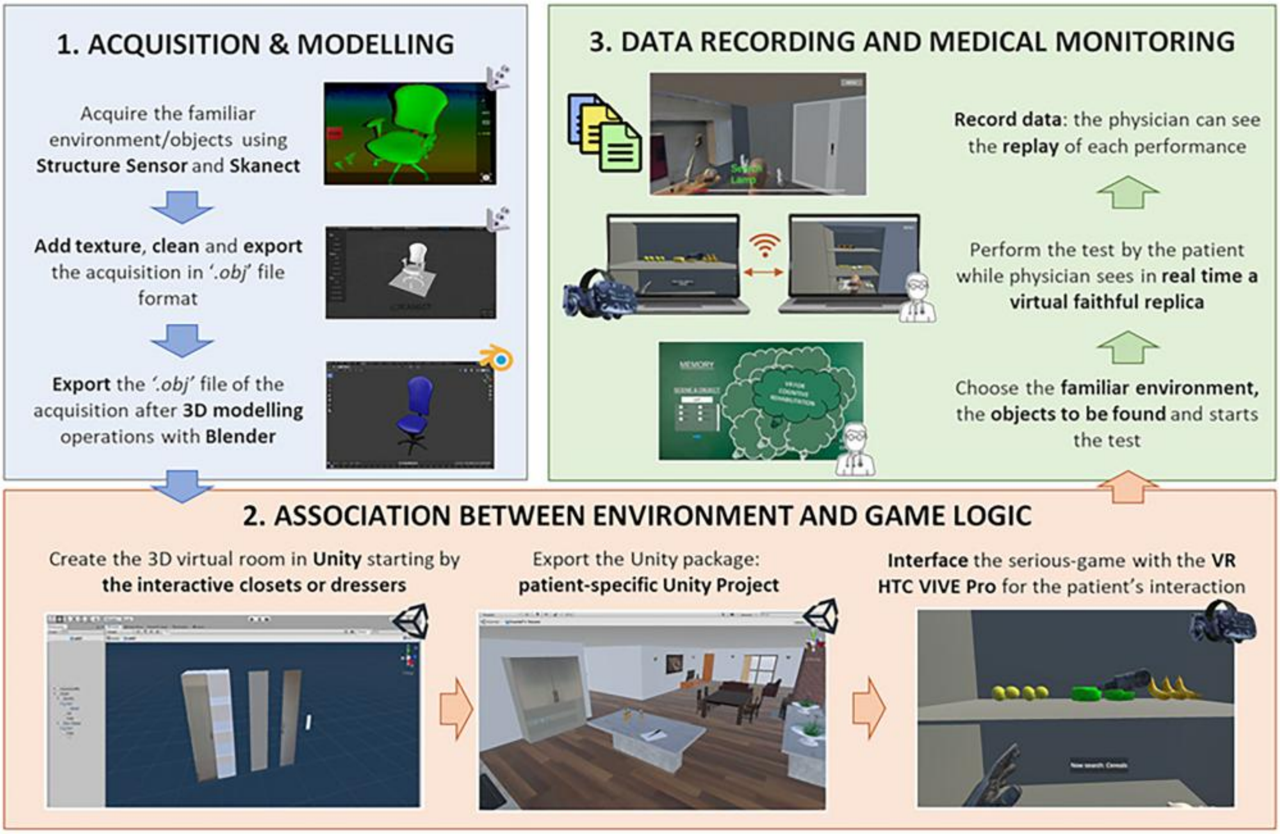

Fig. 7 Three-phase process to develop a patient-specific VR platform for amnesia rehabilitation. Reprinted from Ref. [63].

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Table 2 Readiness of XR adoption by sector based on the reviewed literature

Sector	Readiness level	Main applications	Barriers/challenges
Product design	Medium–high	Conceptual design, virtual prototyping, collaborative reviews, UX simulation	Fragmentation of software/toolchains; limited multisensory integration; lack of interoperable standards
Training (cross-cutting)	High (methodological maturity across domains)	Immersive, repeatable, and safe training for industrial tasks, clinical education, defense, and construction	High cost of hardware; content customization; limited long-term validation; need for faculty/industry expertise
Manufacturing	Medium	Digital twins, ergonomics, human–robot collaboration, "test-before-invest" scenarios, workflow optimization	Integration with legacy systems; scalability; shortage of skilled XR developers; data interoperability
Healthcare	Medium–high	Medical training and simulation, rehabilitation, therapy, remote treatment, patient engagement	Regulatory validation; cost-effectiveness evidence; patient data governance; integration into clinical workflows

domains, such as neuro-motor and cognitive rehabilitation, control of prosthetic devices, and pain and anxiety relief [13].

XR and smart glass technology are emerging as an effective distraction therapy for patients undergoing painful and/or distressing healthcare procedures. As an example, the work of Harper et al. [98] is indicative of a new outlook on technology, which explores women's and obstetrics and gynecology (O&G) healthcare professionals views on the acceptability and preferences for VR as distraction therapy within O&G. In clinical settings, both women's interest in trialing VR and professionals' support of women trialing VR in both O&G settings were predominantly positive.

In general, several studies agree that XR can improve the overall psychological well-being of patients and significantly increase their adherence to rehabilitation plans [52,56]. Patients engaged in interactive and amusing tasks in a virtual scenario can be observed by medical personnel or tracked with motion sensors and evaluated to adjust the tasks to their changing needs and abilities [99,100].

An example is the application described in Ref. [62], addressing retrograde amnesia, a cognitive impairment. Memory loss, or amnesia, can be caused by different conditions such as brain stroke, brain injuries, and psychological disorders. Spatial memory is the form of memory mainly damaged by both ischemic and hemorrhagic brain strokes [101,102]. In cases of retrograde amnesia, the memories before the impairing event are partially or fully lost and frequently cannot be completely retrieved.

In standard rehabilitation practice during hospitalization, patients are typically shown photographs of their home environment to aid memory recovery. Enhancing this approach through an immersive XR experience that reconstructs the patient's home in 3D holds promise for achieving faster and more effective outcomes. Figure 7 shows that the proposed VR system builds on this idea by developing personalized serious games [63]. The main innovation lies in proposing a modular approach, where the game logic remains unchanged and can be applied to any acquired virtual environment. The solution also includes software modules for patient monitoring and data management, enabling automatic generation of rehabilitation reports. This application lends itself naturally to remote therapy, extending rehabilitation beyond hospital discharge. Memory training and monitoring can continue posthospitalization, adapting to the patient's evolving condition. The use of VR contributes to sustained engagement, motivation, and treatment adherence throughout the rehabilitation process.

7 Challenges and Future Trends

The adoption of XR technologies in industry and healthcare has shown remarkable promise, yet several challenges remain on the path to widespread and effective deployment. These challenges span technical, methodological, organizational, and ethical domains and are closely intertwined with the emerging trends that will shape the future of XR. A central theme in the evolution of XR is the integration of advanced technologies such as AI, digital twins, and multisensory feedback systems. XR allows designers to modulate sensory and perceptual stimuli to achieve different levels of immersion and presence. This capability empowers system developers to create personalized and optimized user experiences. However, there is still limited understanding of how combinations of multiple stimuli, visual, auditory, haptic, and olfactory, affect user perception, cognitive load, and task performance. Further research is essential to explore how these modalities interact and contribute to the realism, emotional engagement, and effectiveness of XR applications [19]. These sector-specific trends, levels of maturity, and associated barriers are summarized in Table 2.

The fusion of AI and XR represents a key frontier. AI can enhance XR by enabling intelligent adaptation to user behavior, real-time feedback, and dynamic content generation. Generative AI offers the possibility to automatically create immersive environments and training scenarios tailored to individual users or clinical needs [103,104]. This approach can significantly reduce development time and enable more flexible and scalable XR applications across sectors.

A further dimension that is beginning to redefine the outlook of XR is the emergence of spatial intelligence. Spatial intelligence extends beyond machine vision: it encompasses the ability of AI-enhanced XR to interpret spatial relationships, physical interactions, and environmental dynamics, while also supporting sophisticated forms of interaction and learning within them [105]. With the rapid rise of AI, XR is evolving from immersive visualization toward systems capable of perceiving, reasoning, and adapting to the three-dimensional world and to nuanced user needs. Spatial intelligence also opens the door to personalization through affective computing and behavioral analytics, enabling XR applications to adjust content according to user preferences, habits, and emotional states. In this sense, spatial intelligence constitutes a pivotal frontier: it positions XR systems to evolve from tools of immersion to intelligent collaborators that enhance human perception, decision-making, and interaction with the physical world.

The convergence of large language models with multimodal spatial data holds particular promise. Natural language spatial interfaces, for example, allow users to control virtual objects and environments through conversational commands that reference spatial attributes, requiring systems to ground semantic intent in accurate spatial interpretation. Combined with digital twins and IoT sensor networks, these developments enable XR systems to maintain persistent and shared spatial understanding, integrating semantic scene interpretation, dynamic environmental tracking, and hierarchical spatial memory that ranges from fine object detail to building-scale layouts [31,82]. This evolution redefines digital twins, transforming them from static 3D replicas into dynamic and intelligent entities capable of contextual awareness and adaptive behavior.

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Beyond object manipulation, recent systems have begun to explore the use of large language models to create various XR applications, such as coffee-making tutorials or posture-training assistants, directly within immersive environments from natural language descriptions [106]. By leveraging tool-augmented agents capable of autonomously planning and executing XR applications, this approach removes the conventional design–implementation cycle required by demonstration-based [107–109] or visual-programming [110,111] methods and transforms XR authoring into a conversational process. By substantially lowering the authoring barrier, it democratizes XR creation across domains. More importantly, this shift highlights the potential of large language models not merely as object manipulators but as situated, context-aware assistants capable of delivering adaptive and personalized XR experiences.

From an industrial standpoint, while pilot projects and use-case demonstrations are growing, scaling XR across organizations remains a substantial hurdle. Cost, technical expertise, infrastructure requirements, and resistance to change all hinder wider adoption. Furthermore, the lack of standardized platforms, interoperable tools, and shared best practices impedes the development of coherent XR ecosystems. To address these challenges, comprehensive deployment strategies are needed, including investment in workforce training and technical upskilling, open standards for XR hardware, software, and data formats, and clear evaluation frameworks for assessing return on investment, safety, and usability [91]. In both industry and healthcare, data security and interoperability [89] are also critical concerns. As XR systems become more data-intensive, especially with the integration of wearable sensors and real-time physiological monitoring, robust frameworks for cybersecurity risks [99] and data governance must be established. Beyond technical safeguards, patient data protection in healthcare and worker privacy in industrial environments are critical to building trust and ensuring ethical XR deployment. These concerns extend beyond traditional cybersecurity, encompassing questions of consent, monitoring boundaries, and responsible data usage. Recent studies are focusing on decentralized architectures to tackle those issues [112].

Recent trends in XR hardware point toward greater miniaturization, portability, and multisensory capability. Researchers are actively developing lightweight AR glasses, haptic suits, olfactory modules, and wearable sensors designed to deliver immersive experiences without sacrificing comfort [14,113]. The long-term vision is to create seamless, body-integrated XR setups that function as natural extensions of human perception and action. Key developments include retina-resolution displays and high-fidelity spatial audio, flexible electronics for unobtrusive wearables, exoskeletons and haptic interfaces for physical augmentation, and multimodal sensor fusion for contextual awareness. However, challenges persist in integrating XR with enterprise resource planning systems, real-time sensor networks, and compliance-driven workflows. As Industry 5.0 moves toward human-centric automation, XR will play a key role, provided that data standards, user interfaces, and automation protocols evolve accordingly [3]. In healthcare, XR applications are becoming increasingly sophisticated, yet face unique constraints related to medical validation, regulatory approval, and ethical use. There is a pressing need for domain-specific software development kits, validated simulation protocols, and guidelines for clinical use. Multisensory XR and AI-driven personalization also hold promise for enhancing patient engagement, therapy outcomes, and procedural training. In parallel, the concept of human digital twins is emerging as a transformative tool. By digitally replicating individual users, including motion, physiology, and cognitive state, XR systems can deliver more precise, personalized, and adaptive experiences [76]. This is particularly valuable in rehabilitation, training, and remote collaboration contexts.

In parallel, ethical and societal considerations must not be overlooked. The potential for XR addiction and overreliance raises concerns about mental health and sustainable usage patterns [25]. Equally important is accessibility and inclusivity: XR systems must be designed to accommodate diverse physical abilities, cognitive conditions, and socio-economic contexts to avoid reinforcing digital divides. These issues resonate strongly with recent evidence from mental health research, where AI- and XR-based interventions are being trialed to address rising psychological distress, workforce shortages, and limited access to care [4]. A recent scoping review of AI and XR in metaverse frameworks for mental health reported promising results in terms of patient engagement, symptom reduction, and treatment adherence but also underscored critical risks related to opaque algorithmic processes, data privacy, psychological dependency, and the exclusion of digitally marginalized populations [114]. These insights suggest that while XR and AI hold transformative potential for democratizing access to healthcare and enhancing patient experience, their deployment must be accompanied by robust governance models that prioritize inclusivity, safeguard sensitive data, and mitigate risks of overreliance or inequitable access. These considerations extend equally to engineering contexts, where protecting worker privacy, ensuring inclusivity, and preventing overreliance are essential for fostering trust and sustainable adoption.

Looking ahead, policy initiatives and strategic investments at regional and global levels will strongly influence the trajectory of XR. In Europe, the Digital Strategy highlights that XR could create between 1.2 and 2.4 million jobs by 2025, with up to 800,000 directly related to the technology [115]. The VR/AR Industrial Coalition estimates a 2021 market size of €7.1 billion, expected to grow at around 37% compound annual growth rate to 2026, generating between €20 and €40 billion of added value and up to 860,000 direct jobs in the short term [116]. These figures show that XR is moving beyond experimentation towards industrial-scale deployment. At the same time, the coalition identifies fragmentation of the ecosystem, lack of interoperability, limited 5G and edge coverage, and skills shortages as the main barriers to growth, pointing to the need for standards, investment in infrastructure, and workforce upskilling.

Other regions are also making XR a strategic priority. China's 2022–2026 VR Action Plan [117] aims to expand the domestic XR industry to more than 350 billion by 2026, with explicit focus on industrial applications. In Japan, government and industry collaborations, including the XR Consortium [118] and JETRO initiatives [119], support XR for both entertainment and medical training, while preparing domestic firms for international markets.

8 Conclusions

This article has examined the current trends and future perspectives of XR technologies, encompassing virtual, augmented, and mixed realities, and their growing role in transforming industry and healthcare. After reviewing technological foundations and market trajectories, we analyzed applications across four domains: product design and manufacturing, industrial ergonomics, professional training, and clinical practice. Evidence from case studies and emerging research shows how XR is increasingly enabling human-centered innovation in line with the paradigms of Industry 5.0 and Healthcare 5.0.

Although XR technologies have been widely investigated across domains such as healthcare, education, manufacturing, and aerospace, the existing literature remains largely descriptive. A search in the Scopus database retrieved 9,341 review articles published between 2020 and 2026 using the following query:

```
TITLE-ABS-KEY(“extended reality” OR XR OR
“augmented reality” OR AR
OR “virtual reality” OR VR OR “mixed reality” OR
“immersive reality”)
AND PUBYEAR > 2019 AND PUBYEAR < 2027
AND ( LIMIT-TO ( DOCTYPE,“re” ) )
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Despite this impressive volume of reviews, there is still a lack of quantitative performance comparisons (e.g., between major engines such as Unity and Unreal), cost-effectiveness analyses, and standardized benchmarks. One reason for this absence is that most XR research to date has been exploratory, focusing on proof-of-concept prototypes and sector-specific pilots rather than systematic cross-platform evaluations. Studies typically emphasize demonstrating feasibility or highlighting qualitative benefits (e.g., engagement, safety, usability), while rigorous quantitative benchmarking across platforms, devices, and sectors requires standardized protocols, large-scale testing environments, and long-term investment. Moreover, XR deployments are highly context-dependent: healthcare, manufacturing, and aerospace each impose unique constraints (e.g., regulatory requirements, hardware integration, fidelity needs), making it difficult to establish generalizable cost-effectiveness analyses or standardized benchmarks. As a result, comparative performance data and economic evaluations have lagged behind the descriptive and conceptual literature. To address this gap, the present article introduces a comparative "readiness by sector" intended to guide future empirical research.

Looking ahead, XR is expected to converge with Digital Twins, Artificial Intelligence, and edge computing, creating adaptive and distributed platforms for training, treatment, and industrial operations. Remote collaboration will be supported by shared virtual spaces, intelligent assistants, and real-time data integration. Achieving this vision will require sustained investment in research, infrastructure, and education, together with close cooperation among engineers, clinicians, designers, human factors experts, and policymakers.

At the same time, important gaps and challenges remain. These include interoperability limitations, the absence of standardized evaluation metrics, and barriers to scalability. We also highlight future research priorities such as cross-sector benchmarking, ethical frameworks, and inclusive design strategies. Finally, several grand challenges persist, including balancing immersion with cognitive load and integrating XR into legacy systems, which must be addressed to enable widespread adoption.

In conclusion, XR is moving toward more immersive, intelligent, and personalized systems that augment human capabilities across domains. Overcoming the identified gaps and challenges will be essential to move XR beyond isolated pilots and toward integrated infrastructures that support sustainable innovation, resilient organizations, and equitable access in both industry and healthcare.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

No data, models, or code were generated or used for this article.

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