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ANTHROPOMORPHIC ROBOTS IN CONSTRUCTION: A COMPREHENSIVE REVIEW AND ANALYSIS FOR DEPLOYMENT

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SUMMARY: *Humanoid robots, as technologically advanced anthropomorphic machines, are designed to mimic human movements and forms, making them suitable for dynamic and complex environments. Despite this robotic technology potential, their adoption within labor-intensive industries remains limited, primarily due to technological, economic, and operational barriers. This paper systematically reviews humanoid robots' key characteristics, applications, and challenges within the construction domain. Through scientometric and content analyses, it explores existing limitations and methodologies for integrating humanoid robots effectively while spotlighting simulation techniques as a critical driver for development in construction. The review examines technical constraints such as energy inefficiency, motion adaptability, and environmental challenges, alongside potential solutions through simulation-driven design and optimization strategies. To understand the robotic-technology challenges and benefits in the physical environment, examples of deployed simulations are presented. Developed in immersive environments, the simulations emphasize aspects of the design, testing, and deployment of these robotic systems (humanoid prototypes) by enabling digital representations of real-world scenarios, and improvements in human-robot collaboration (HRC). This paper seeks to bridge the gap between humanoid robotics and construction applications by offering a review and analysis for stakeholders and identifying potential avenues for future research. The insights contribute to a better understanding of the advancements in humanoid capabilities and their transformative potential. It aims to promote technology and encourage innovative solutions in task automation within the construction industry by minimizing the risks of innovation in traditional tasks, as well as envisioning collaborative workflows.*

KEYWORDS: *humanoids, simulation, anthropomorphic robots, human-robot collaboration (HRC), human-robot interaction (HRI), virtual reality (VR), immersive environments, construction tasks, humanoids in construction tasks.*

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1. INTRODUCTION

Humanoid robots are designed to mimic human movements and forms (anthropomorphic features), characterized by high adaptability and flexibility, essential for performing a wide range of human-operated tasks. These features make humanoid robots particularly valuable for dynamic and complex environments like construction sites. Their anthropomorphic design typically includes a head, torso, arms, and legs, enabling the seamless integration of robots into human environments by facilitating navigation, optimizing space use, and utilizing existing tools to accomplish tasks. These attributes allow humanoid robots to tackle diverse tasks where human-like adaptability and agility are required. Furthermore, their human-like physical characteristics and functional similarities with the human body significantly influence human perceptions and behaviors toward these robots, fostering natural and intuitive interactions, critical for creating effective human-robot collaboration (Nazir et al., 2023; Rodriguez-Guerra et al., 2021).

Emerging factors like rising urbanization, an aging workforce, and the demand for safer, more efficient construction systems continue to drive the development and improvement of humanoid robotics. Robots are increasingly utilized for high-precision tasks such as material handling, tunnel inspections, and façade installation. Their integration with complementary technologies, including Building Information Modeling (BIM) and augmented reality (AR), fosters improved operational planning and streamlined workflows by enabling real-time updates throughout project phases. Experts have identified robotic applications across multiple construction phases like demolition, production, installation, and maintenance, highlighting the potential for cost-saving opportunities and facilitating principles of circular economy, such as recycling and disassembly (Carra et al., 2018).

Despite technological advances, humanoid robots have yet to gain traction in production floors and construction sites due to major challenges, including technical constraints, safety concerns, operational inefficiencies, and high economic costs. Economic barriers are among the most cited obstacles for the adoption of robotic technology (Davila Delgado et al., 2019; Oke et al., 2024; Vaduva-Sahhanoglu et al., 2016). These concerns are further exacerbated by the fragmented nature of the construction industry and its variable complexity (Davila Delgado et al., 2019; Huang et al., 2021; Law et al., 2022; Pradhananga et al., 2021), as well a lack of awareness and readiness among stakeholders (Mahbub, 2008).

Technical limitations are also critical. Developing humanoids with complex systems, including multiple actuators, sensors, stereo vision, and human-machine interface technologies, involves highly sophisticated processes that are hindered by functional limitations and high costs. For instance, NASA/DARPA's Robonaut demonstrated difficulties in achieving efficient autonomous control and real-time perception for complex tasks, primarily due to limitations in tactile sensing and force/torque interactions (Diffler et al., 2003). Despite their anthropomorphic design, which makes them suitable for dynamic environments, humanoid robots are not yet able to handle the specific demands of construction tasks such as material handling, hazardous operations, and human-robot collaboration. Enabling robots to navigate highly unstructured environments, characteristic of construction workplaces, remains a critical limitation (Ardiny et al., 2015; Brosque et al., 2020).

Furthermore, current development lacks systematic validation methods, such as simulation, to overcome limitations related to adaptability, real-world performance, precision, and task-specific integration. Simulations serve as a pivotal step in conceptualizing and testing humanoid systems in environments closely approximating real-world conditions by providing controlled spaces for experimentation and refinement before deploying humanoids into operational settings. Bridging the gap between robotic innovation and construction applications requires a deeper understanding of simulation methodologies and their potential to enable safe, efficient humanoid deployment in unstructured environments.

This paper advances understanding of the opportunities and constraints of humanoid robots by presenting a systematic review of existing humanoid prototypes, their applications in construction environments, and key barriers to adoption. The authors examine humanoid capabilities and limitations, analyzing their challenges and benefits, alongside the critical role of simulations as a methodological platform for enhancing humanoid technology. Specifically, this research includes a systematic review of simulation applications in humanoid robotics development. Simulation-driven frameworks, including immersive virtual reality (VR) environments and task-specific modeling techniques, can enhance the adaptability, precision, and operational efficiency of humanoid robots, enabling them to overcome technical and environmental constraints in construction tasks (Zahabi & Abdul Razak, 2020). Specifically, deploying humanoid prototypes into simulated construction scenarios can refine their design, optimize human-robot collaboration (HRC), and improve performance in dynamic and hazardous environments, ultimately facilitating broader adoption and integration into the construction industry. The scientometric analysis and content analysis methods guide this exploration, offering comprehensive assessments of humanoids' suitability, adaptability, and cost-effectiveness in unstructured environments. Researchers and engineers benefit from this study by identifying potential humanoid performance in unpredictable, dynamic construction tasks.

Analysis of construction activities in unstructured environments also reveals similarities with manufacturing operations, as the design of construction processes involves controlled resource transformation into tangible outcomes. Construction and manufacturing share principles related to skilled and unskilled labor use, raw material processing, and operational constraints, including sustainability challenges like waste reduction and energy efficiency. These intersections underline the mutual potential for exploring advanced robotic innovations across industries. While previous studies, such as Ikuabe et al. (2023), explored the potential applications and benefits of humanoids in construction scenarios, including a focus on South African perspectives, this paper further delves into the technical advantages and challenges associated with humanoid robots in dynamic construction environments. By using manufacturing applications for humanoid robots as foundational case studies, this paper provides robust insights into optimizing humanoid robotics for construction, fostering transferable strategies and scalable solutions (Everett & Slocum, 1994).

The following are this research's contributions: (1) a comprehensive review of humanoid prototypes and their potential applications in construction tasks; (2) exploration of simulation methodologies as platforms for evaluating humanoid adaptability and feasibility; (3) identification of trends and research gaps using systematic literature reviews and scientometric analyses; (4) examination of humanoids' technical advantages and challenges within construction workflows; and (5) strategic recommendations and actionable insights for stakeholders, emphasizing future research directions for humanoid adoption in dynamic industries.

This paper is organized as follows: first, an overview of the historical evolution of humanoid robots and current prototypes. Next, the adaptation of humanoids to construction environments is discussed. The role of simulation tools in supporting robotic integration is then examined. The findings from a comprehensive systematic literature review are presented using visualization software, including charts and network maps. Finally, the concluding analysis offers reflections on the adaptation of humanoid technology for construction tasks, with the authors outlining future research directions and actionable steps for industrial stakeholders.

2. DEFINITION AND ORIGINS OF HUMANOIDS

A humanoid robot is an autonomous or semi-autonomous machine designed to physically and functionally resemble humans, typically with a head, torso, two arms, and two legs, enabling it to perform complex tasks and interact naturally with its environment (Fareh et al., 2021; Vukobratovic et al., 2004). Unlike traditional industrial robots, which are confined to repetitive tasks in highly structured settings, humanoid robots are engineered for dynamic and unstructured environments through advanced motion control systems, comprised of sensors, actuators, and sophisticated planning and control algorithms, that allow real-time interaction and adaptation (Gupta et al., 2006). The concept of humanoids dates back to antiquity and early myths, but was first brought to mechanical reality in ancient times, such as Hero of Alexandria's wine-pouring machine (AD 50) and Leonardo da Vinci's 15th-century mechanical knight (Denny et al., 2016). The 20th century saw the emergence of electrically powered humanoids, such as Elektro by Westinghouse in 1937, followed by significant milestones, including Wabot-1 (1973) (Takanishi, 2019), which could walk and communicate, and Sony's Qrio and Honda's ASIMO, which marked leaps in perception, locomotion, and interaction. Across history, humanoid robots have served not only as marvels of technological advancement but also as versatile research platforms for machine learning, human-robot interaction (HRI), and autonomous decision-making, with modern applications expanding into healthcare, rehabilitation, education, manufacturing, space exploration, and service industries (Denny et al., 2016; Eaton, 2007; Fareh et al., 2021; Vukobratovic et al., 2004).

2.1 Taxonomy characteristics

Humanoid robots can be classified into five key dimensions, offering insights into their design, capabilities, and applications. (Kim et al., 2024; Saeedvand et al., 2019). These categories are morphology, functional classification, level of autonomy, control systems and actuation methods, and sensor integration. Below, the authors explore these dimensions in detail, with a focus on morphology-based and autonomy-based classifications as primary categories.

2.1.1 Morphology

Humanoid robots have evolved as artificial entities inspired by human form to mimic human motion, tasks, and interactions. Their origin lies in the philosophical and technological pursuit of creating artificial species, as highlighted by the concept of simulated evolution. This approach, akin to Darwin's theory in "The Origin of Species," laid the groundwork for developing robots with traits and functional adaptability through artificial chromosomes (Yoo et al., 2009). Morphologically, these robots are characterized by their human-like appearance, often incorporating a head, torso, two arms, and two legs. This design choice stems from advances like early mechanical automata and modern developments such as ASIMO by Honda and HanSaRam, a continually evolving humanoid robot series designed since 2000 at KAIST to emulate human posture and behavior (Yoo et al., 2009). However, variations in morphology can also be observed, including robots with additional limbs or simplified forms to optimize specific tasks, such as those used in industrial environments.

Functional classification is equally significant in understanding the diversity of humanoid robots, as these robots fulfill roles ranging from research and industrial assistance to education, healthcare, military, and entertainment. For example, Pepper (Pandey & Gelin, 2018) is specifically tailored for customer interaction and assistance, showcasing advancements in humanoid capability for human-robot interaction. On the other hand, Atlas (Atlas, 2022; Hodson, 2013) exemplifies the pinnacle of high-mobility applications, engineered for search and rescue missions requiring robust physical performance and agility. Together, these humanoids represent the dynamic evolution in morphology and applications, all rooted in an ongoing effort to capture elements of human functionality in artificial species. Humanoids can range from fully teleoperated systems, where every action is directly controlled by a human operator, to fully autonomous robots that use advanced AI to perceive, decide, and act independently in complex environments (Onnasch & Roesler, 2020). Semi-autonomous robots combine the two, using operator guidance while executing certain tasks autonomously.

2.1.2 Control systems and actuation methods

A control system in humanoid robotics refers to the set of algorithms and models responsible for generating, coordinating, and applying control signals that enable the robot to perform complex and dynamically feasible movements, often involving high-level planners along with low-level real-time controllers (Lutz et al., 2025). Actuation methods describe the technologies and mechanical strategies by which forces and motions are produced and transmitted to the robot's joints, fundamentally determining how robot movement is generated and executed. Hydraulic systems are known for their power and are used in robots that require high strength, such as those performing heavy lifting tasks. Pneumatic systems are often employed for lightweight and flexible movements, while electric actuation, characterized by precision and efficiency, is widely used in robots designed for dexterous tasks (Unbehauen, 2009). The choice of actuation method not only influences motion capabilities but also impacts energy consumption, noise, and maintenance needs. Besides traditional technologies, modern humanoids are increasingly adopting advanced actuation techniques that use closed-loop or parallel mechanisms. In these systems, actuation occurs by transmitting motion and force from motors, which are positioned away from the joint, through kinematic linkages such as four-bar linkage mechanisms.

2.1.3 Degrees of freedom (DoF)

A cornerstone concept in humanoid robotics, DoF defines the robot's capacity for movement and its ability to replicate human-like actions (Vukobratovic et al., 2004). A robot's DoF refers to the number of independent parameters needed to describe its motion. For humanoid robots, achieving realistic motion involves implementing a high number of DoF across various parts of the body, such as the head, arms, legs, and torso.

In humanoid arms, each joint typically contributes a specific range of motion, with the shoulder offering three DoF (pitch, roll, and yaw), the elbow providing one DoF (flexion/extension), and the wrist contributing another two or three DoF for rotation and articulation. A highly functional humanoid arm may therefore require six to seven DoF to perform tasks like grasping, manipulating objects, or interacting with tools.

2.1.4 Degrees of freedom in humanoid robots

A robot's degrees of freedom (DoF) represent the number of independent parameters required to characterize its movement. In the context of humanoid robots, achieving lifelike and functional movement relies on incorporating a large number of DoF distributed throughout distinct regions of the robot's body. These regions typically include the head, arms, legs, and torso. Each part contributes multiple DoF, enabling complex, realistic motion patterns that mimic human actions.

The integration of numerous DoF across the humanoid's body enables the robot to perform tasks such as walking, manipulating objects, and interacting with its environment in a natural manner. By precisely controlling these independent motion parameters, humanoid robots can replicate the flexibility and range of motion observed in humans, supporting their ability to adapt to diverse tasks and environments.

Legged locomotion adds an additional layer of complexity; each leg may feature six or more DoF to accommodate hip, knee, and ankle movements, enabling the robot to walk, climb stairs, and adapt to uneven terrain. Advanced locomotion requires precise coordination of multiple joints, dynamic balance maintenance, and the ability to recover from destabilizing forces. Robots like Atlas or ASIMO (Hirose & Ogawa, 2007) incorporate sophisticated gait algorithms and real-time feedback systems to manage these challenges. In addition to limb movement, the torso and head of a humanoid robot often contribute several DoF. The head may include multiple DoF for neck movement (pitch, yaw, and roll) to simulate looking around or focusing on specific objects. Meanwhile, the torso may offer rotational or bending capabilities to enhance flexibility during tasks that require reaching or bending.

Overall, the total DoF in humanoid robots varies widely, ranging from around 20 DoF in simpler models to over 50 in highly advanced systems. For instance, the Atlas humanoid robot boasts over 30 DoF, allowing for fluid and dynamic movement, while robots like Sophia (Riccio, 2021) prioritize facial DoF to simulate human-like expressions and social interaction. The challenge lies not only in designing enough DoF but also in managing them effectively. This requires real-time control algorithms that balance computational efficiency with precise motion control, often leveraging AI and machine learning for optimization.

2.2 Examples from the origins to the present developments

The history of humanoid robots traces back to early literary inspirations and has since evolved into a sophisticated field of robotics. One of the earliest references to robots appears in Čapek and Kallinikov (1940) the play *Rossum's Universal Robots*, which coined the term 'robot' and depicted biological androids, human-like beings designed for labor (Fukuda et al., 2017). This spark in literature laid the groundwork for decades of research focused on replicating human behaviors across physical, cognitive, and social areas.

In the 1960s, a significant technical breakthrough came with the development of the Zero Moment Point (ZMP) stability theory by Miomir Vukobratović. This concept provided the basis for humanoid robots to achieve balanced bipedal locomotion, which led to the creation of WABOT by Ichiro Kato at Waseda University in Japan, the first humanoid robot capable of walking (Fukuda et al., 2017). This era marked the beginning of humanoid robotics as a scientific discipline, attracting researchers interested in replicating human-like movements.

Fast forward to the late 1990s and early 2000s, Honda's ASIMO became one of the most iconic humanoid robots, demonstrating sophisticated capabilities such as climbing stairs and maintaining balance (Fukuda et al., 2017). ASIMO's advancements captivated the public and the robotics community, solidifying the idea that robots could eventually integrate into human society. Around the same time, Europe made strides in humanoid robotics with projects like iCub, an open platform to study human cognitive development through robotics (Metta et al., 2010). Boston Dynamics, a US-based company founded in 1992 by Marc Raibert after spinning off from the MIT Leg Lab, entered the field in 2008 with the PETMAN, a robot designed for testing chemical protective clothing for the US Army. This robot was one of the first to achieve human-like mobility and dexterity, such as walking at human speeds and performing calisthenics (Nelson et al., 2019). PETMAN laid the groundwork for developing the Atlas robot, which debuted in 2013. Atlas was designed to navigate rugged outdoor terrains and was equipped with enhanced balance mechanisms using angular momentum. Its ability to walk over rough terrains and climb stairs marked a leap in humanoid robot capabilities (Nelson et al., 2019).

The DARPA Robotics Challenge (DRC) 2015 represented a watershed moment in humanoid robotics. Robots like DRC-Hubo from South Korea demonstrated innovative designs, such as the ability to switch between walking and rolling, highlighting the potential of humanoid robots in disaster response (Guizzo & Ackerman, 2015). This competition underscored the growing importance of human-robot collaboration (HRC) and the ongoing challenges of achieving fully autonomous operations. In summary, humanoid robotics has evolved from theoretical concepts in the mid-20th century into a vibrant, multidisciplinary field today. Advances in control algorithms, artificial intelligence, and bipedal locomotion have enabled robots to replicate complex human tasks, and ongoing research is focused on improving autonomy, perception, and interaction in real-world scenarios (Nelson et al., 2019). Figure 1 illustrates a timeline of humanoids' evolution.

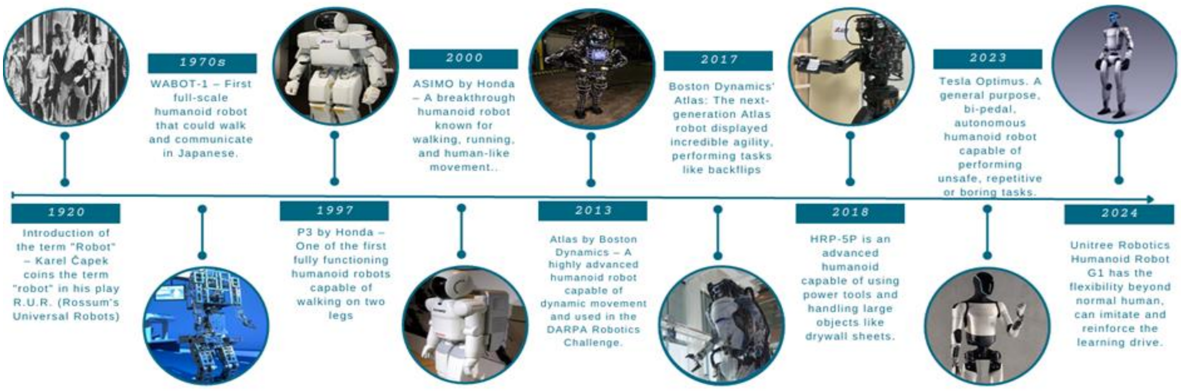


Figure 1: Evolution of humanoids timeline.

The most recent humanoid robots are presented in Table 1 highlighting their key features, applications, affordability, versatility, and advancements in functionality. It provides a brief overview of their capabilities across domains such as industrial automation, logistics, healthcare, and human interaction. For example, to describe a few of the most popular prototypes, Tesla Optimus, also known as the Tesla Bot, enhances automation by taking on dangerous, repetitive, and physically demanding tasks traditionally performed by humans. Featuring a human-like design with advanced mobility, dexterity, and a payload capacity of up to 20 kilograms, Optimus integrates Tesla's proprietary technologies, such as autopilot cameras, neural net planning, and a fully self-driving computer. These innovations enable the robot to improve flexibility and scalability in manufacturing and construction, addressing challenges such as labor shortages and safety risks. Optimus is particularly suited for complex construction environments, where its advanced balance algorithms, perception capabilities, and motor control can help tackle tasks on uneven terrain and manipulate tools effectively. However, successful commercialization will depend on Tesla delivering a practical and reliable product that outperforms competitors (Malik et al., 2023; Su, 2023). In 2024, the robotics community saw a groundbreaking development: Unitree unveiled its G1 humanoid robot. Priced competitively with manipulator arms, the G1 represents a significant leap in making humanoid robots accessible to a broader range of research laboratories and institutions. Designed with advanced electrically actuated joints and leveraging modern deep reinforcement learning (DRL) algorithms, the G1 excels in generating and implementing complex motions with remarkable stability and precision. Its introduction is poised to catalyze progress in humanoid robotics, similar to the advancements observed in drones and quadrupedal locomotion over the past decade (Unitree Robotics, 2024).

Launched in 2025, NVIDIA's Isaac GR00T N1 further advances the field as the first open, fully customizable foundation model designed specifically for generalized humanoid reasoning and skills. Architected with dual systems for both fast-thinking actions and methodical decision-making, GR00T N1 enables robust performance across a range of real-world tasks, such as grasping, manipulation, and object transfer, by leveraging training from diverse human and robotic data sources. Its embodiment-aware AI supports highly adaptive behaviors, allowing deployment in dynamic settings including industrial, service, and collaborative environments. The introduction of GR00T N1, alongside hardware like the Jetson Thor, marks an important milestone toward the vision of general-purpose, highly versatile robot agents (Bjorck et al., 2025).

Exoskeletons (Pons, 2008) and humanoid robotics represent a transformative advancement in construction and the built environment by augmenting human capabilities and addressing complex, unstructured work settings. As Bock et al. (2012) highlighted, these systems' cutting-edge technologies, such as power augmentation, motion sensing, and cognitive enhancement, to support human-robot cooperation. With applications ranging from prefabrication and assembly tasks to facility management and hazardous construction scenarios, exoskeletons and humanoid robots bridge the gap between structured and dynamic environments, enhancing efficiency and safety. Moreover, advancements in autonomy, tele-operation, and adaptive control systems are enabling these robots to perform tasks independently or collaboratively with humans, especially within construction sites, urban infrastructure, and extreme conditions such as space exploration. These tools not only multiply human strength but also integrate intelligence, adaptability, and modularity, paving the way for robotics to reshape construction processes and services in the built environment.

Table 1: Top humanoid robots as of 2025 overview (capabilities, applications, and potential suitability for construction tasks).

Humanoid Name(Reference)	**Capabilities**	**Year of Creation**	**Construction Task (Y/N)**
Nvidia GR00T N1	Fast-thinking actions and methodical decision-making.	2025	Y(Limited)
Optimus Gen 2 (Tesla)	AI-driven task automation, factory operations	2023	N
Atlas (Boston Dynamics)	High mobility, dynamic balance, navigation in challenging environments, research, disaster response	2013	N (Retired)
HRP-5P (AIST)	Drywall installation, heavy lifting, autonomous walking, construction tasks	2018	Y
Digit (Agility Robotics)	Bipedal mobility, AI-driven navigation, load carrying	2019	N
T-HR3 (Toyota)	Safely assist humans in homes, medical facilities, construction sites, disaster areas, and outer space.	2017	Y (Limited)
G1 (Unitree Robotics)	Lightweight, programmable, educational robot for research and training	2023	N
GR-1 (Fourier Intelligence)	Strong mobility, AI task management, precision, industrial automation	2023	Y (Limited)
4NE-1 (NEURA Robotics)	Industrial and domestic adaptability, high-strength, AI decision-making	2022	N
CyberOne (Xiaomi)	Emotion recognition, customer service, vision-based navigation	2022	N
Figure 02 (Figure AI)	High-speed industrial tasks, precision, optimized AI for manufacturing	2024	Y (Limited)
Walker S1 (UBTECH Robotics)	Multitasking, navigation, office and home assistance	2024	N
ARMAR-4	Autonomously perform maintenance, detect partner needs, and assist	2012	Y(Limited)
NEO (1X Robotics)	Personal companion, smart home integration, caregiving support	2024	N
SE01 (EngineAI)	Exceptional flexibility, AI-driven motor control, acrobatics	2024	N
Phoenix (Sanctuary AI)	Human-like dexterity, general-purpose AI, Carbon™ AI for reasoning, versatile task execution	2023	Y (Limited)
WALK-MAN (IIT)	Tool handling, dexterous movements, disaster response	2015	Y (Limited)
Talos (PAL Robotics)	Full-body force control, object manipulation	2017	Y (Limited)
iCub (IIT)	Grasping, cognitive learning, research-focused	2004	N

2.3 Laboratory deployments of humanoids and potential applications in construction

Humanoid robots in construction are currently limited to research and controlled demonstrations. The implementations focus on practical applications focused on specific, repetitive, or assistive tasks. Examples include Honda's ASIMO (Hirose & Ogawa, 2007), or Boston Dynamics' Atlas. These artifacts have shown their ability to lift and carry lightweight materials or operate tools in controlled environments. These prototypes have been used to study how robots can assist human workers in hazardous or labor-intensive tasks. Their current role is more supportive than autonomous, serving as a step toward integrating robotics into construction workflows, particularly in tasks that require mobility and interaction in human-like environments.

Despite the relatively early stage of research in humanoid robotics, prototypes have shown significant progress in performing repetitive tasks traditionally carried out by humans (Dario et al., 2001). It can be envisioned that humanoids can undertake hazardous tasks such as demolition or rebar tying, significantly reducing the risk of injury for human workers by navigating dangerous environments with the aid of advanced sensors (Gonsalves, 2023). Their precise operations would enhance construction quality, minimize material waste, and reduce the need for rework.

Notably, a few humanoids presented in Table 1, such as HRP-5P and GR-1, exhibit potential for construction-related applications, leveraging their advanced mobility, AI-driven automation, and precision in task execution. Table 2 provides an in-depth analysis of the key potential advantages of humanoids, including autonomous operation, efficient heavy-load handling, and task-specific customizations that improve safety and productivity. Each robot's technology is associated with specific strengths, such as autonomy, precision, and advanced sensors, which enhance task execution in construction environments.

Table 2: Potential technological advantages of humanoid robots in construction.

Humanoid Robot	Technological Advantages	Advantages of Construction Tasks
The HRP-5P's *(Kaneko et al., 2019)*	Autonomous task execution using 3D mapping and localization. Advanced multimodal sensors for adaptive grasping. Precise control for heavy load handling.	Handles heavy loads like plasterboard. Autonomous execution reduces risks in repetitive and hazardous tasks. Effective in fine motor tasks like screwing.
ARMAR-4 *(Asfour et al., 2013)*	Modular and lightweight design with 63 DOF for high dexterity. Robust torque control for precise movement. Integrated sensors for enhanced perception.	High dexterity for precise tool and material manipulation. Capable of complex bimanual tasks like assembling components.
GR-1 (Fourier Intelligence) *(Ackerman, 2024)*	Highly bionic body with predefined motions for twisting, squatting, and gripping. Powered by LLM for intuitive human-robot conversations and task automation. Smart Actuator (FSA): Integrates motor, driver, and encoder into a single module.	Advanced perception systems for navigating construction sites and identifying materials. High peak torque (230 Nm) suggests capability in handling moderately heavy objects. Speed (5 km/h) is adequate for moving around construction sites.
ATLAS Unplugged ***(Nelson et al., 2019)***	Advanced sensing with multiple cameras and LIDAR. Dynamic adaptability to rough terrains. Error recovery and stability under challenging scenarios.	Wireless operation enhances mobility in disaster zones. Advanced perception aids in navigation and performing complex tasks.

The implementation in the construction industry has potential applications, yet some characteristics may hinder their full potential on projects. Humanoids such as the HRP-5P and GR-1 demonstrate potential for task automation and precision, yet they are much slower and less efficient than human workers. Their performance is further limited by operational and design constraints, including kinematic constraints, battery life, calibration, and the complexity of real-world operation. Although Atlas Unplugged operates autonomously and is equipped with advanced sensing capabilities, it exhibits high energy consumption, limited stability-to-speed trade-offs, and communication challenges. Table 3 summarizes the challenges, limitations, and disadvantages of using humanoid robots for construction tasks. Practical implementation remains constrained by challenges such as task-specific precision, environmental adaptability, and human-robot collaboration.

These limitations underscore the critical role of simulations in envisioning future prototypes and applications in construction. It is expected that simulation helps to motivate concepts for construction applications, enabling researchers to refine designs, anticipate challenges, and optimize humanoid functionality for future real-world integration. By utilizing advanced simulation techniques, researchers and engineers can explore novel design ideas, validate critical parameters, and ensure the optimization of systems before they are physically produced. Simulations enable the identification of crucial factors for design validation and optimization, including stress resistance, motion control, and environmental adaptability. They facilitate prototyping within innovation cycles so that potential design flaws and safety risks can be identified and mitigated early. This iterative process of technology refinement ensures the creation of scenarios with humanoid robots for future deployments on-site.

Simulation techniques offer significant opportunities to enhance efficiency, accuracy, and safety in construction robotics by addressing challenges posed by unstructured environments (Chu et al., 2008). These methods refine iterative processes for tasks like arc welding, adhesive applications, and paving, enabling faster project completion, reduced material waste, and improved safety. By leveraging immersive tools such as AR/VR, researchers can refine robotic adaptability and optimize operations, while integrating AI and machine learning further enhances precision and versatility across construction and humanoid robotics development.

Using AR/VR simulations is essential for testing and refining activities. These immersive technologies allow for detailed scenario planning and performance evaluation. AR/VR technologies have been developed to explore interactions between humans and robots and understand task allocation in human-robot collaboration (HRC) environments (Bänziger et al., 2018; Eswaran et al., 2023). Beyond their role in enhancing processes, simulations also have significant educational value, providing students and new engineers with practical learning tools to understand the complexities of humanoid robotics. Through simulations, learners can better understand the challenges of real-world applications, such as navigating dynamic environments or interacting with other robots and humans.

Table 3: Humanoid robot limitations in construction.

Humanoid Robot	Technological Limitations	Disadvantages of Construction Tasks
The HRP-5P's *(Kaneko et al., 2019)*	Slow task execution, up to 8 times slower than humans. Kinematic and motion dynamics limitations. Limited walking speed (1 km/h).	Inefficient compared to humans for large-scale projects. Performance degrades in unpredictable environments. Need further speed and motion planning improvements.
ARMAR-4 *(Asfour et al., 2013)*	Potential torque and load limitations for heavy-duty tasks. Limited information on outdoor and rough terrain capabilities. High complexity in control algorithms for real-time adjustments.	May struggle with heavy or overly large construction materials. Performance in harsh or unstable environments is uncertain. High complexity can lead to increased setup and maintenance time.
ATLAS Unplugged *(Nelson et al., 2019)*	High energy consumption limits operational time. Prioritizes stability, resulting in slow movement. Communication challenges in disaster settings.	Heavy weight reduces agility and efficiency in confined spaces. Requires skilled operators for complex tasks. Limited maneuverability in tight areas.
GR-1 (Fourier Intelligence) *(Ackerman, 2024)*	Dependence on technology risks overlooking human skills and expertise. Limited payload capacity:10-15 kg. Dependence on pre-programmed tasks.	Real-world construction environments can be harsh, unpredictable, and involve heavy materials that may test the robot's limits. Needs assessment on rugged terrain handling, exposure to elements like dust and moisture.

3. SCIENTOMETRIC AND CONTENT ANALYSIS

In the following section, the authors provide an overview of the methodology for the systematic review, followed by the scientometric analysis and the content analysis.

3.1 Methodology

The presented study adopts a systematic approach to analyzing trends in humanoid robotics research, specifically focusing on humanoid simulations in construction tasks. The methodology integrates scientometric analysis with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to ensure a rigorous, replicable, and comprehensive review of the literature (Kastrin & Hristovski, 2021). The authors used a series of phases outlined in the methodology for this research, as shown in Figure 2. These phases involve extracting, analyzing, and interpreting quantitative data from scientific publications. The process includes collecting bibliographic data such as authorship, citations, keywords, and publication sources, followed by applying statistical and computational techniques to identify patterns, trends, and relationships within the literature. It starts with an initial search using predefined keywords like anthropomorphic robots, human-robot collaboration, and simulations in manufacturing and construction. The search produces a broad set of results, which are then manually reviewed to ensure relevance to the research focus.

In line with the PRISMA guidelines, a multi-stage selection process was followed to refine the set of studies. The initial search returns 77 papers, from which 20 are selected based on inclusion criteria: relevance to humanoid simulations in construction tasks, peer-reviewed status, and publication in English. Papers were excluded if they were non-academic or unrelated to the research focus. The search terms were specifically refined to concentrate on anthropomorphic robots, human-robot collaboration, and simulations in manufacturing and construction (Page et al., 2021). The topic content of these papers explores how simulations in immersive environments contribute to human-robot collaboration (HRC) and task readiness, covering a broad range of topics, from anthropomorphic robots to specialized robotic systems such as manipulator arms, and emphasizing their practicality and economic benefits. The PRISMA flow diagram in Figure 3 illustrates the selection process and clarifies the inclusion and exclusion criteria (Haddaway et al., 2022).

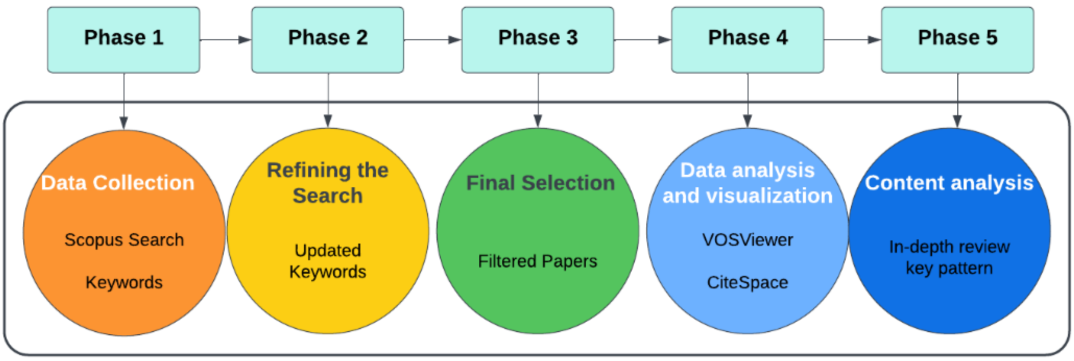


Figure 2: Methodology phases.

Statistical and computational techniques were applied to identify patterns, trends, and relationships within the literature. These frameworks allowed researchers to gain valuable insights into the structure, development, and impact of the scientific field, guiding further research and decision-making. The final phase synthesizes the findings and interprets them in the context of humanoid robot applications in construction. Insights gained from the bibliometric data offer valuable guidance for identifying gaps and emerging trends in humanoid robotics simulation. By integrating PRISMA with scientometric methods, this study ensured that the review process was not only systematic and replicable but also capable of providing deep insights into the current state and future directions of humanoid robotics research in construction tasks.

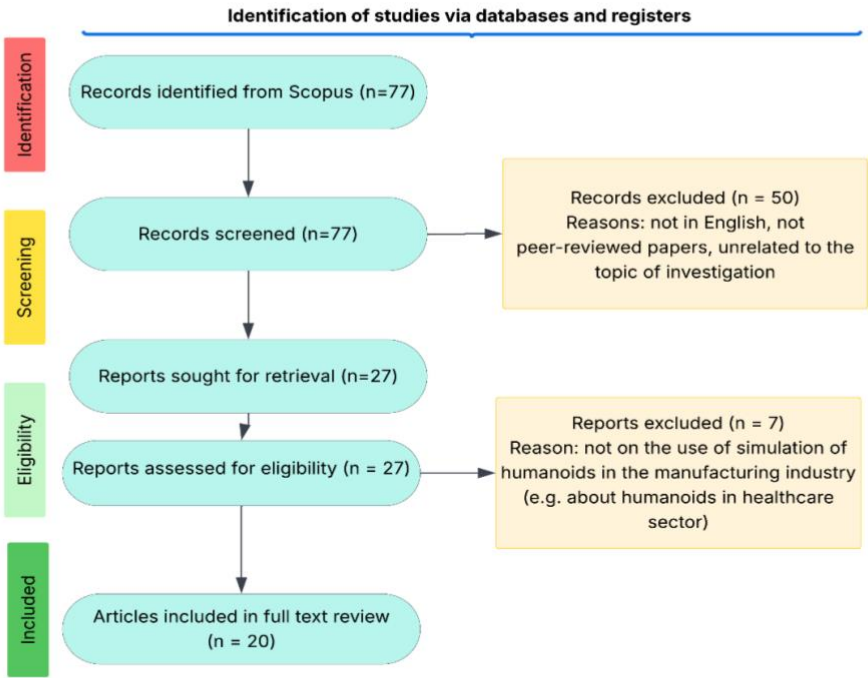


Figure 3: PRISMA Flow Diagram (Page et al., 2021) (inclusion and exclusion criteria).

3.1.1 Phase 1: Data collection

Scopus, a multidisciplinary bibliographic database, was used to search for articles on humanoid simulation for construction tasks. The initial search was conducted using the keywords (TITLE-ABS-KEY ("humanoid" AND "simulation" AND "construction" OR "AEC"), which returned 95 papers. Since the goal was to get a broad picture of the field, this initial search was not restricted to any document type (e.g., journal article, conference paper) or other criteria. The abstracts of these papers were manually reviewed to evaluate the relevance of their content and the appropriateness of the search terms. During this process, it became evident that the search terms were not ideal since the keyword "construction" was pulling up papers about building humanoids and their components or algorithms for humanoid movements. Therefore, the initial relevance was low, with few papers directly addressing humanoid simulations for construction tasks.

3.1.2 Phase 2: Refining search

To improve the search results, the authors updated the keywords to: (TITLE-ABS-KEY ("anthropomorphic robotic" OR "anthropomorphic robots" OR humanoid OR "human robot" OR "robot worker") AND TITLE-ABS-KEY ("manufacturing industry" OR fabrication) AND TITLE-ABS-KEY (simulation OR "virtual reality" OR "immersive environment"). The initial search revealed papers using different terms (e.g., anthropomorphic robot) to refer to the same type of robot, making it essential to incorporate synonyms into the search. Additionally, the authors added "manufacturing" to the keyword list to exclude unrelated sectors such as healthcare and social services. Finally, the refinement incorporated related terms like "virtual reality" and "immersive environment" to better capture simulations. This refinement, as shown in Figure 4, returned 77 papers, focusing more on human-robot collaboration (HRC) and simulations using virtual reality (VR) to study robot processes.

Figure 4: Bibliometric analysis keywords.

3.1.3 Phase 3: Final selection

The authors conducted a systematic review of related literature following PRISMA guidelines to ensure methodological rigor and transparency. The initial search identified 77 papers, of which 57 were excluded based on document type, language, or lack of relevance to humanoid simulations in construction. The inclusion criteria required that the papers be written in English, peer-reviewed, and published in academic journals, ensuring quality and focus while excluding books and non-academic sources. From the remaining 27 papers, the abstracts and content were manually evaluated for relevance and quality, resulting in the final selection of 20 papers that specifically aligned with the research aims. These papers emphasized the role of simulations in immersive environments in facilitating human-robot collaboration (HRC) and task readiness.

The selected papers were sorted into thematic subsets to guide analysis. One subset focused on simulating anthropomorphic robots, or "humanoids," in virtual environments to optimize performance prior to real-world deployment. Another subset included studies on specialized robots, offering lessons transferable to humanoids, such as advancements in motion dynamics, task efficiency, and safety design. This systematic approach and thematic classification created a solid foundation for studying how humanoid robotics can be integrated and its potential to enhance construction processes through simulation and collaboration strategies.

3.1.4 Phase 4: Data analysis and visualization

The data analysis was conducted on the final selection of relevant articles. The analysis includes a description of the basic characteristics of the papers, such as publication year, authors' discipline, and country of origin. Scientometric analysis was performed to identify trends and patterns of keywords and authorship connections. For this purpose, the authors used VOSviewer (van Eck & Waltman, 2010) and CiteSpace (Chen, 2016) as bibliometric tools. However, only VOSviewer was employed to visualize keyword co-occurrence and networks. This software helped uncover authorship and publication patterns (Niazi, 2016). These tools were instrumental in mapping the progression of knowledge within the field.

3.1.5 Phase 5: Content analysis and topical focus

The final stage of the analysis consisted of a more in-depth analysis of the selected papers. The authors evaluated and synthesized each paper's main contributions. They categorized the papers based on their main themes, such as Simulation and Human-Robot Interaction (HRI), and examined the connections between these topics. The content analysis was included to provide readers with a clearer understanding of the current state of the literature on humanoid simulation and to identify areas for future research.

The framework used was adapted from workflow guidelines found in Aria and Cuccurullo (2017), Cobo et al. (2011), and Zupic and Čater (2014), as shown in Figure 5. By leveraging these tools, researchers gained valuable insights into the structure, development, and impact of focused scientific endeavors.

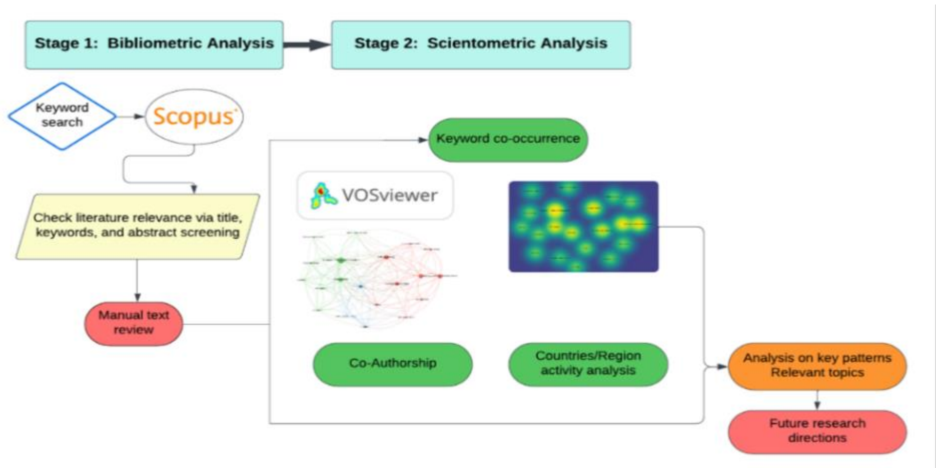
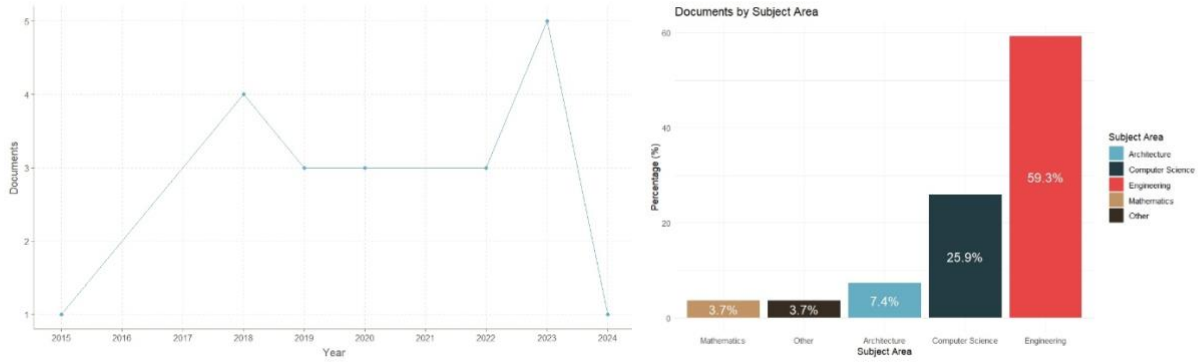


Figure 5: Framework analysis.

3.2 Scientometric analysis

The outcome of the study mapped trends in humanoid robotics and simulation research. This approach highlights key themes and collaboration networks, providing an overview of the scientific landscape in this domain. As shown in Figure 6 (a), the growth of this type of scientific production from 2015 to this date (without being able to count 100% of the number of publications for 2024) is still developing. However, the researchers observed a steeper trend since 2018, when the number of papers of this type increased fivefold.

Most contributions in this field are from engineering and computer science, as shown in Figure 6 (b). Specifically, 59.3% of the papers are from engineering, 25.9% from computer science, and the rest from mathematics, architecture, and other disciplines. This result probably reflects the interdisciplinary nature of the field, where engineering and computer science play key roles in topics like robotics and automation. The shared methodologies and tools used by professionals in these fields could explain why these categories are often discussed in relation to such topics.



Papers contribution from 2015 to 2024. *Papers by subject area.*

Figure 6: Papers by year and subject area.

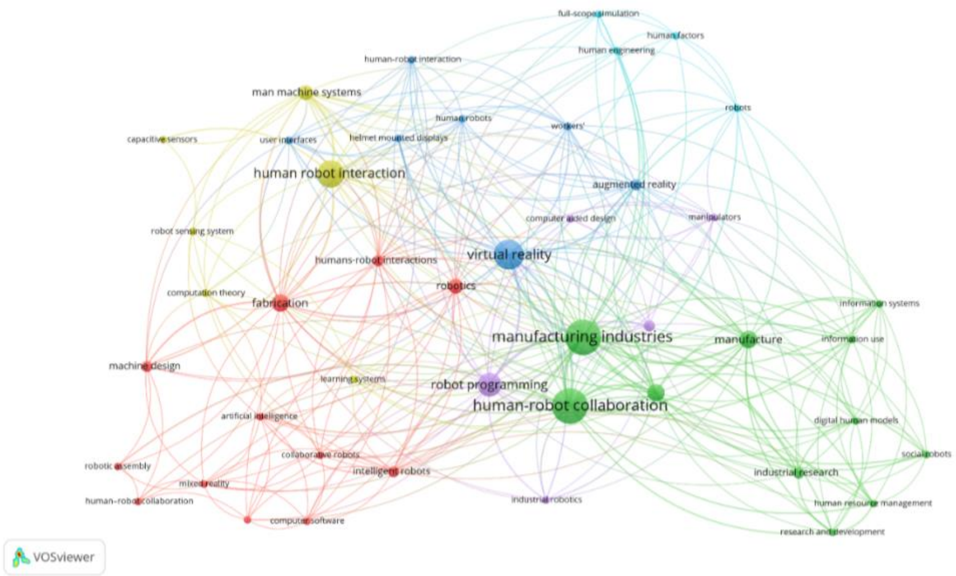


Figure 7: Examples of all-keyword co-occurrence network with a threshold of 45.

Keyword co-occurrence analysis was used to connect knowledge domains related to humanoid or anthropomorphic robot simulation in immersive environments while considering human-robot collaboration. Co-occurrence links knowledge areas by identifying keywords that often appear together in academic publications, indicating a conceptual relationship between them. By mapping these co-occurrences, the analysis reveals how different research areas overlap and interact, highlighting key areas of interdisciplinary integration. Distance-based maps were created using VOSviewer to indicate the strength of the link between these fields. Narrow gaps between knowledge domains suggest stronger connections. The size of each object tag corresponds to the number of publications where the keyword appears.

Figure 7 combines both author keywords with Scopus auto-indexing keywords. It shows that "human-robot collaboration" emerged as the term most connected to other keywords, and “human-robot interaction” and “virtual reality” also appear highly connected. The implications of this research for humanoids are significant, as it suggests that humanoid robots are increasingly being integrated into industrial environments where collaboration with humans is essential.

3.3 Content analysis

While scientometric analysis reveals overarching trends and connections in literature, content analysis provides a deeper understanding of specific contributions. By examining key studies, this section identifies practical advancements and lessons applicable to humanoid robotics in construction.

Simulation frameworks have proven effective for optimizing human-robot collaboration (HRC), particularly in dynamic and unpredictable construction contexts. Configurable frameworks allow real-time task scheduling and conflict resolution, enabling better coordination of hybrid teams (Antakli et al., 2020). Digital Human Models (DHMs) further enhance the realism of simulations, aiding in the planning and assessment of interactions between humans and robots (Zhu et al., 2019). Studies on cyber-physical systems integrating human workers, robots, and enterprise information systems highlight the potential of simulation in ensuring safe and efficient collaboration, as demonstrated in manufacturing intralogistics (Gursch et al., 2018).

The use of augmented and virtual reality (AR/VR) has facilitated immersive safety training and task preparation in construction. Virtual safety training systems create risk-free environments, preparing workers and robots for collaborative tasks (Dianatfar et al., 2020). Similarly, mixed-reality interfaces have been employed to enable synchronous collaboration between robots and human workers, improving precision and flexibility in construction processes (Shen & Hsu, 2023). For example, AR systems for collaborative fabrication provide in-situ task instructions, enhancing communication and trust between humans and robots (Reilly et al., 2016). These technologies allow robots to perform complex tasks, such as timber fabrication, in controlled environments before deployment on construction sites (Bossecker et al., 2023).

Developments in tactile sensor simulations have advanced humanoid robotics, enabling precise manipulation of materials and tools in construction. Research on capacitive sensors ensures robots can interact safely with their environment and human collaborators, addressing key safety and efficiency challenges (Schoffmann et al., 2022). Adaptive robots equipped with machine learning and computer vision are also being explored for their ability to autonomously navigate and manipulate diverse construction materials in real-time (Kuts et al., 2019). Co-simulation techniques that combine formal verification with 3D simulation provide robust methods for ensuring the safe collaboration of humanoid robots and human workers in high-risk environments like construction sites (Askarpour et al., 2020).

Simulation has also played a critical role in addressing cognitive and sensory challenges in humanoid robotics. Research on simulating cognitive development, inspired by models like the multimodal infant framework, offers innovative methodologies for enabling humanoid robots to perceive and interact with their surroundings effectively in unstructured environments (Mattern et al., 2022). Sensory-based robotic systems incorporating tacit knowledge further enhance robots' ability to perform delicate tasks in construction (Wuzella, 2022). A comprehensive framework for 3D simulation of hybrid teams in production environments highlights the importance of modeling and optimizing human-robot interactions (Antakli, 2018). These studies demonstrate the potential of simulation to make robots more intuitive and capable collaborators in industries that rely on dynamic human-robot interactions. Lastly, the development of advanced tactile sensors, such as the four-capacitor tactile sensors, has been crucial for enabling humanoid robots to handle delicate objects with precision. This is particularly important in construction, where robots must manipulate various materials and tools. Research by Cheng et al. (2023) has provided solutions for improving tactile sensor accuracy, ensuring robots can perform their tasks with the required precision in demanding environments.

3.4 Topical focus

This section explores the topical categorization and innovation highlights of Virtual Reality (VR), Human-Robot Interaction (HRI), humanoid robotics, and robotic fabrication, emphasizing their collective role in advancing human-robot collaboration and automation. This information is summarized in Table 4, which provides a comprehensive overview of key studies and their contributions to these interconnected fields.

Table 4: Relevant papers' categorization areas.

Areas	References
Virtual Reality (VR)	(Zhu et al., 2019); (Yang et al., 2023); (Etzi et al., 2019); (Gallala et al., 2022); (Han, 2023); (Apraiz Iriarte et al., 2022); (Dianatfar et al., 2020); (Bossecker et al., 2023)
Human-Robot Interaction (HRI)	(Antakli, 2018); (Buxbaum et al., 2018); (Chiriatti et al., 2022); (Antakli et al., 2020); (Zhu et al., 2019); (Gursch et al., 2018); (Yang et al., 2023); (Etzi et al., 2019); (Gallala et al., 2022); (Schoffmann et al., 2022); (Apraiz Iriarte et al., 2022); (Deniša et al., 2023); (Kuts et al., 2019); (Askarpour et al., 2020); (Dianatfar et al., 2020); (Buxbaum et al., 2019)
Humanoid Robots & Simulation	(Reilly et al., 2016); (Bedaka & Lin, 2018); (Hale et al., 2019); (Mattern et al., 2022); (Schoffmann et al., 2022); (Wuzella, 2022); (Cheng et al., 2023)
Fabrication & Assembly	(Shen & Hsu, 2023); (Yang et al., 2023); (Adel, 2023); (Bossecker et al., 2023)

The intersection of four key topics that stood out after analyzing the content of the reviewed papers: Virtual Reality (VR), Human-Robot Interaction (HRI), Humanoid Robots and Simulation, and Robotic Fabrication and Assembly. These fields converge around the shared goal of enhancing anthropomorphic features in robotic systems, with significant implications for the construction industry.

The definitions of these key topics follow.

3.4.1 VR and HRI

Immersive technologies improve collaboration by simulating complex environments and providing real-time feedback. Studies highlight the use of VR in training and testing human-robot interactions (Apraiz Iriarte et al., 2022; Yang et al., 2023).

3.4.2 Humanoid robots and simulation.

Simulations improve robots' ability to operate safely and efficiently in construction, emphasizing sensory-based systems for delicate tasks and environmental adaptation (Schoffmann et al., 2022; Wuzella, 2022).

3.4.3 Robotic fabrication and assembly

Robotic fabrication and assembly refer to the use of robotic systems to autonomously or semi-autonomously perform construction-related tasks such as cutting, welding, drilling, or assembling structural components. These systems are increasingly integrated with simulation platforms to ensure task precision, minimize human error, and enable pre-deployment testing.

Using simulation-driven approaches allows developers to optimize robotic workflows before physical implementation, reducing costs and increasing safety on job sites. For example, mixed-reality and digital twin technologies have been shown to enhance these systems by enabling real-time feedback, spatial awareness, and coordination between human operators and robots. For instance, Adel (2023) and Shen and Hsu (2023) developed a collaborative mixed-reality interface that enables humans and robots to perform synchronized timber fabrication tasks, demonstrating improved flexibility and task accuracy. Similarly, Bossecker et al. (2023) introduced a VR-based simulator for industrial robotic arms used in wood fabrication. This allowed precise programming and visualization of tool paths, reducing material waste and increasing safety before actual fabrication began. These examples demonstrate that simulation tools were employed not only to improve precision but also to enhance communication between robots and human collaborators during fabrication. Simulation also facilitates iterative design by enabling rapid testing of tool configurations, joint tolerances, and material constraints. As construction moves toward mass customization and prefabrication, robotic fabrication and simulation-driven planning become essential for enabling adaptive, responsive, and efficient construction practices.

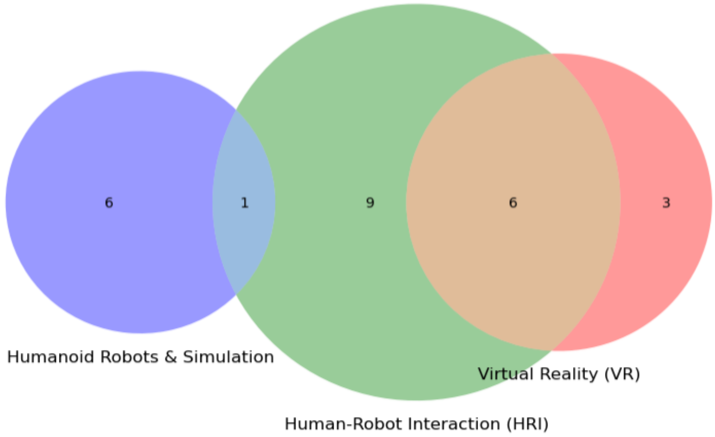


Figure 8: Overlap between VR, HRI, and Humanoid Robots and Simulation.

Figure 8 shows a visual representation of the existing scientific repertoire's topical intersections. It shows the largest intersection that occurs between HRI and VR, where six papers explore how immersive environments enhance human-robot collaboration, as seen in works like Etzi et al. (2019) and Yang et al. (2023) that emphasize VR's role in improving robot interaction testing. Only one paper focuses on HRI and Humanoid Robots & Simulation, discussing human collaboration with simulated robots, such as Reilly et al. (2016) work on robotic systems. Lastly, three papers are dedicated solely to VR, like Shen and Hsu (2023) one that examines mixed-reality interfaces for robot fabrication without involving HRI or humanoid robots.

This representation scale of advancements in each topical area and the development within human-robot interaction as an overarching area of study. The analyzed papers provide evidence of the impact of these connections, and these intersections motivate researchers and show research needs on adaptable robots for human-centric tasks.

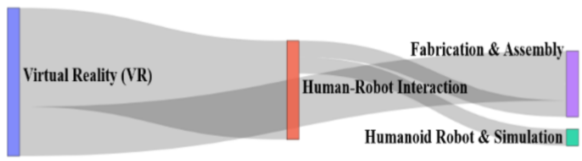
3.4.4 Topical analysis

The HRI, as an overarching area of study for humanoid applications, focuses on optimizing collaboration through simulation frameworks, digital twins, and real-time interaction mechanisms that enhance task efficiency and safety. For example, studies investigate how digital twins enable real-time feedback and better control in dynamic industrial workflows (Antakli, 2018; Gallala et al., 2022). Research on humanoid robots emphasizes multimodal sensory frameworks, capacitive sensor simulations (CapSense) (Schoffmann et al., 2022), and advanced digital twin technologies to ensure humanoids can respond to unpredictable scenarios and operate safely (Wuzella, 2022). Similarly, studies in robotic fabrication and assembly demonstrate how mixed-reality interfaces enable synchronous collaboration between humans and robots, allowing for precision and flexibility in nonstandard tasks such as construction and fabrication (Adel, 2023; Shen & Hsu, 2023). Figure 9(a) illustrates the topical heatmap, which shows the distribution of papers across four categories from 2015 to 2024. The X-axis represents the publication years, while the Y-axis lists the categories, with color intensity indicating the number of papers per category each year.

Key trends include a notable rise in VR papers in 2023 and consistent representation of HRI across several years, peaking in 2018 and 2023. Humanoid Robots and Simulation saw concentrated activity in 2022 and 2023, while Robotic Fabrication and Assembly had a smaller but steady presence. The heatmap also highlights intersections between categories, particularly in 2023, where papers span multiple fields, showcasing growing interdisciplinary research.

The Sankey diagram shown in Figure 9(b) provides a clear visualization of how papers overlap across four categories: The width of the flows between the categories represents the number of papers that belong to both categories. Notably, a significant flow between VR and HRI indicates that many papers explore how virtual reality enhances human-robot interaction. A smaller but notable flow extends between VR and Robotic Fabrication & Assembly, showing papers focusing on how virtual technologies assist in robotic assembly tasks.

(a) Heatmap of the category distribution.



(b) Sankey diagram: overlapping categories.

Figure 9: Topical category analysis across scientific papers.

There is also a direct connection between HRI and humanoid robots and simulation, reflecting papers that examine human-robot collaboration using humanoid robots. This connection is crucial as humanoid robots, with their anthropomorphic features, are often designed to mimic human behavior closely. Overall, the Sankey diagram illustrates the interdisciplinary nature of the research, with substantial overlap between VR and HRI and some across other categories, highlighting key areas of innovation in robotics and immersive technologies.

4. DISCUSSION

Having analyzed the current state of research through scientometric and content analysis, the implications of these findings focus on how the insights gained can inform the design, testing, and deployment of humanoid robots in construction, highlighting key opportunities and remaining challenges. The findings point to simulations as the first exploratory tool that would allow researchers to design, test, and refine HRI scenarios, without the implications of using physical robots or real-world environments, especially in hazardous or hard-to-access settings such as construction sites. When analyzing simulations from the review, several lessons that are transferable to the construction industry are summarized in Table 5.

From the review, existing research highlights critical simulation factors that would be essential for deploying humanoid robots in construction environments. The role of simulation in refining robot design is to ensure the success of task-specific capabilities and to understand how the automated tasks impact the operations performed by humans. This underlines the importance of enhancing HRI research to explore the effect on all aspects of traditional operations and the transition to more automated tasks, enabling safe and efficient collaboration. For example, key areas where simulations help assess how robots handle dynamic conditions, and potential risks on-site include environmental adaptability and safety testing.

Another key takeaway from the review is the importance of sensor and perception accuracy, multi-robot coordination, and replicating real-world conditions to prepare robots for practical challenges. Simulation platforms are also highlighted for their role in testing design, movement, and task performance, ultimately ensuring that humanoid robots can meet the demanding standards of construction applications.

Elattar (2008) elaborates, the construction industry, a labor-intensive and risky domain, has embraced robotics and automation to enhance safety, efficiency, and performance. Yet, integrating VR/AR technologies alongside automation for predictive modeling has proven to be a technical challenge. Furthermore, Elattar (2008) and Kamath and Sharma (2019) emphasize that as urbanization increases, envisioned intelligent applications for construction robotics must balance two imperatives: their economic feasibility and technological rigor, particularly in dynamic and hazardous work environments (Cao, 2024; Chikwendu et al., 2023; Tong et al., 2024). It is worth noting that simulation introduces challenges as they do not perfectly transfer to real-world conditions, including technical issues such as latency and sensor noise, and human cognition behavior modeling for real-world human-robot interactions.

Table 5: Critical factors of simulations for humanoid robots' deployments in construction environments.

Key Factor	Description	Relevance to Humanoid Robots in Construction
Design and Prototyping	Refining and testing humanoid robot designs, improving efficiency performance and reducing costs before physical prototyping (Shen & Hsu, 2023).	Helping developers fine-tune design aspects like balance, mobility, and task-specific tools (e.g., welding or lifting) before committing to costly prototypes (Shen & Hsu, 2023).
Task-Specific Simulations	Ensuring that robots can handle precise roles, such as material handling or assembly (Etzi et al., 2019).	Ensuring that robots can manage specific construction tasks like welding, bricklaying, or timber fabrication in real-time on a construction site (Kuts et al., 2019) and (Etzi et al., 2019).
Human-Robot Interaction (HRI)	Modeling how robots interact with humans, especially in collaborative environments like construction, where robots and humans work together (Gallala et al., 2022).	Ensuring humanoid robots can safely and efficiently work alongside human workers in construction environments, minimizing risks and improving collaboration (Gallala et al., 2022).
Environmental Adaptability	Adapting to changing environmental conditions is tested via dynamic simulations that mimic real-world changes like weather or moving obstacles (Antakli, 2018).	Simulating weather changes, shifting terrains, and moving workers help prepare humanoid robots to adapt and maintain functionality in real-world conditions (Antakli, 2018).
Failure and Safety Testing	Preemptively identifying where humanoid robots might fail and assess the safety of their operations (Antakli et al., 2020).	Allowing developers to test high-risk construction tasks and address potential dangers, such as robot instability on uneven ground or when handling heavy loads (Antakli et al., 2020).
Sensor and Perception Systems	Ensuring accurate perception and navigation in complex environments with sensor systems (e.g., cameras, lidar, infrared) to (Schoffmann et al., 2022).	Detecting obstacles, identifying objects, and navigating construction sites safely. Simulating sensor data enables the refinement of these systems (Schoffmann et al., 2022).
Multi-Robot Coordination	Testing the coordination between multiple robots working together in a collaborative environment (Shen & Hsu, 2023).	Coordinating tasks like lifting, welding, and inspecting by testing how robots can efficiently coordinate tasks and reduce delays (Shen & Hsu, 2023).
Replication of Real-world Conditions	Mimicking real-world conditions, such as construction sites, to test robot adaptability and performance before deployment (Antakli, 2018).	Preparing humanoid robots for the specific challenges on-site, including terrain variability, material obstacles, and worker interactions (Antakli, 2018).
Simulation Platforms	Creating high-fidelity simulations to test robot design, movement, and interaction using software tools like Unity or Gazebo (Antakli et al., 2020).	Allowing developers to test humanoid robots' movements, environment interactions, and task execution, ensuring that robots meet performance and safety standards (Antakli et al., 2020).

4.1 Immersive simulation of construction tasks examples

To exemplify the effects of simulation, illustrative 3D-based immersive simulation (built in Unity) (Wang et al., 2010) is shown in Figure 10, Figure 11, and Figure 12. These simulations allow observations for inferences about the feasibility and relevance of humanoid robots performing common everyday high-risk construction tasks. The simulations feature high-fidelity humanoid robot models (e.g., Boston Dynamics' Atlas) and include basic locomotion, inverse kinematics, and scripted interactions for the task environment. These immersive simulations facilitated understanding of the critical factors (as in Table 5) to convey the potential effects of humanoid robots in substituting human labor in physically hazardous construction tasks. The simulating tasks were also designed to examine the construction process, the role of humanoids, and to aid future training, ergonomic research, or task automation prototyping. The two scenarios modeled were overhead drilling, as shown in Figure 10, and abrasive sandblasting, as shown in Figure 11. They were selected based on their high ergonomic strain, repetitive nature, or respiratory health hazards for human workers. Overhead drilling involves static postures and overhead exertions that significantly contribute to musculoskeletal disorders (MSDs) in construction workers, as discussed in Xu et al. (2022), which identifies such tasks as priority areas for robotic assistance due to their physical demands and repetitive stress.

Figure 10: Overhead drilling in the immersive simulation.

For abrasive blasting, the risks are more severe. Radnoff and Kutz (2014) reported that "two-thirds of the workers assessed were potentially over-exposed to respirable crystalline silica," and even silica substitutes contained undisclosed amounts of crystalline silica, posing a persistent threat for occupational silicosis. Similarly, Madl et al., (2008) emphasize that chronic exposure during sandblasting may lead to "emphysema, chronic bronchitis, mineral dust airway disease, and reduced pulmonary function," affirming the need to mitigate human involvement in such tasks. Another simulation to study the impact of repetitive tasks and automation is drilling tasks, as shown in Figure 12.

Figure 11: Abrasive sand blasting in the immersive simulation.

From the simulation study, achieving model accuracy is critical, as simulations are inherently as reliable as the data and models they employ. Inaccuracies adopted from poor modeling or insufficient data can lead to unforeseen challenges during the transition to real-world applications, impacting the efficiency and feasibility of simulated solutions (Leite et al., 2016; Taher, 2021). High-fidelity simulations, while beneficial, demand significant computational resources, raising concerns about cost and accessibility. Furthermore, closing the gap between simulated outcomes and real-world performance demands rigorous testing on physical systems, particularly for robotic applications that must adapt to unpredictable, dynamic environments.

Figure 12: Repeated drilling task in the immersive simulation.

In alignment with the challenges highlighted by Mutis et al. (2024), developing realistic and precise simulations in immersive environments is particularly demanding. Addressing the complexity and dynamics of construction sites is required. More realistic and practical simulations of the physical environment require considering the changes in position or velocity of objects materials, equipment, and workers. Others to consider include the unpredictability of the physical environment, such as uneven surfaces. Simulations themselves are an ongoing research gap between reduced simplifications and less risky and uncertain robotics prototype deployments in the real world, critical for the case of humanoid operations in construction sites. The aim is to have fewer effects of technology sensing variations, including those related to the discrepancy between simulated and real-world robotic capability. For example, simplifying the simulation of environmental variables, such as uneven material surfaces, saves computational resources but overlooks complex interactions like friction, material elasticity, and deformability, which may result in unrealistic robot behaviors when prototypes are physically deployed.

4.2 Future work and action points

To advance the integration of humanoid robotics into construction, future research should focus on leveraging simulation environments to address the industry's unique challenges. Task-specific simulations, tailored to activities such as welding, masonry, and material handling, are critical for refining robot capabilities and testing their adaptability to dynamic construction environments. These simulations must account for real-world variables like changing weather, uneven terrain, and interactions with human workers. Moreover, developing real-time co-simulation platforms, incorporating virtual reality (VR), augmented reality (AR), and digital twins, can bridge the gap between laboratory settings and on-site applications, enabling iterative testing and optimization of humanoid designs under near-realistic conditions (Hassija et al., 2024). A promising avenue for future research is the integration of machine learning algorithms within simulations to enhance robots' ability to learn and adapt to complex tasks and unforeseen scenarios. Multi-robot coordination also needs further research, as construction tasks often require collaboration between humanoids and other robots, such as drones or quadrupeds. Simulating these interactions can optimize task allocation, communication protocols, and workflow efficiency.

For practitioners and stakeholders, the recommendation is to adopt a phased deployment strategy. Risks can be minimized by starting with controlled environments, such as warehouses or prefabrication facilities, and progressively introducing robots to more complex job sites, and robot performance can be iteratively improved. Simulations should also emphasize safety-critical scenarios, enabling stakeholders to refine fail-safe mechanisms and ensure compliance with industry safety standards. Combining these technical advancements with VR/AR-based training programs for workers can foster familiarity, build trust, and improve collaboration between humans and robots on-site.

Assessing the economic feasibility of deploying and operating a humanoid robot for construction tasks is another important factor. Stakeholders can use simulation-driven cost-benefit analyses to evaluate the return on investment (ROI), considering potential labor savings, improved safety, and faster project completion. It is essential to compare the performance of humanoids not only with human workers but also with existing construction industry. This comparison will provide insights into whether humanoid robots truly offer a superior performance compared to alternatives such as automated machinery, drones, or traditional robotic systems. Given the high costs of humanoid robots, it is especially important to assess if their additional capabilities justify the investment or if other technologies could deliver similar benefits at a lower cost.

5. CONCLUSION

The presented work addresses the potential transformative applications of humanoid robots in the construction industry, emphasizing their anthropomorphic design, adaptability, and suitability for dynamic construction environments. Through a systematic review reinforced by scientometric and content analysis, the findings shed light on the current technological advances and critical limitations of this robotic technology that have impact when considering future adoption. While humanoid robots' demonstrations have been successfully deployed in controlled environments, their implementation on active construction sites remains constrained by several operational, technical, and economic barriers. This review identifies research areas of interest after incorporating simulations as a key first step to identify strategies to conceptualize robotic operations before transitioning to real-world applications.

The significance of employing simulation-based methodologies is underscored as pivotal in shaping the future of humanoid deployment. Simulations enable extensive testing under near-real conditions, facilitating the identification of design flaws and task readiness while optimizing energy efficiency, motion adaptability, and environmental responsiveness. By mimicking construction scenarios such as hazardous operations and material handling, simulations guide researchers in refining humanoid functionality for high-risk, unstructured environments. Additionally, the growing integration of virtual tools, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), further bridges the gap between theoretical capabilities and operational construction workflows. These immersive methods not only enhance robot adaptability but also improve collaboration, trust, and interaction between humans and humanoids by fostering worker training and streamlining task allocation.

Highlighted throughout the review is the centrality of human-robot collaboration (HRC), which plays a foundational role in integrating innovative technologies into labor-intensive industries. Researchers must continue to develop humanoid systems capable of navigating dynamic environments while maintaining intuitive communication with human collaborators, ensuring seamless teamwork is essential to production efficiency. The content analysis revealed critical insights into refining sensory frameworks, perception systems, and machine learning algorithms to empower humanoid prototypes with adaptive decision-making and contextual awareness. Furthermore, humanoids' ability to emulate human motion and handle intricate tasks can significantly lower workplace hazards and optimize labor costs, hallmarks of economic sustainability and safety improvements in construction.

While the review focused on technical factors, it is essential to address ethical issues such as privacy concerns caused by advanced robotic sensory systems and potential disruptions to the workforce. Beyond technological innovation, stakeholders need to develop ethical standards and retraining programs for workers to adapt to changes in industry practices. Proactive approaches like phased deployment strategies are crucial for reducing risks and balancing automation with the economic realities of the construction industry. By initially deploying humanoids in prefabrication facilities or warehouse settings, their efficiency and adaptability can be gradually improved, facilitating incremental adoption across diverse construction projects. The potential collaboration with complementary robotic technologies, including drones and robotic arms, offers another promising way to overcome operational constraints. Simulation-driven coordination frameworks can facilitate experimental scheduling and task distribution among different robot types, boosting construction workflow productivity. Additionally, advancements in tactile sensor technology, adaptive motors, and digital twin simulations hold the potential for rapid progress in robotic dexterity and site adaptability. Future multidisciplinary efforts combining robotics, computer science, engineering, and construction will lead to fully autonomous systems that integrate sensor accuracy, real-world reliability, and human-centered task efficiency. In conclusion, this study highlights that humanoid robots have significant potential to transform construction processes through task automation, improved precision, and better collaboration. Their future use depends heavily on research-driven advances in simulation technologies, ongoing innovation to improve environmental adaptability, and ethical considerations for harmonious integration. The construction industry will increasingly need safer, more efficient, and sustainable methods to boost productivity while meeting strict industry standards. When thoroughly researched, ethically applied, and technologically refined, humanoid robots can provide extraordinary benefits in speeding up construction innovation. This study serves as a guide to help integrate humanoid robots into transformative workflows in construction by connecting research with real-world applications, ensuring scalable, human-centered, and forward-looking solutions for construction automation.

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REFERENCES

Ackerman, E. (2024). Year of the Humanoid: Legged robots from eight companies vie for jobs. IEEE Spectrum, 61(01), 44-48. https://doi.org/10.1109/mspec.2024.10384544

Adel, A. (2023). Co-Robotic Assembly of Nonstandard Timber Structures 42nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA 2022), https://deepblue.lib.umich.edu/handle/2027.42/178286

Antakli, A., Spieldenner, T., Köster, M., Groß, J., Herrmann, E., Rubinstein, D., Spieldenner, D., & Zinnikus, I. (2020). Optimized Coordination and Simulation for Industrial Human Robot Colla. Lecture Notes in Business Information Processing. https://doi.org/10.1007/978-3-030-61750-9_3

Antakli, A. H., Erik; Zinnikus, Ingo; Du, Han; Fischer,Klaus (2018). Intelligent Distributed Human Motion Simulation in Human-Robot Collaboration Environments. Proceedings of the 18th International Conference on Intelligent Virtual Agents. https://doi.org/10.1145/3267851.3267867

Apraiz Iriarte, A., Lasa Erle, G., Serrano Muñoz, A., Elguea Aguinaco, Í., & Arana Arexolaleiba, N. (2022). Evaluation of the user experience of an industrial robotic environment in virtual reality Proceedings from the International Congress on Project Management and Engineering, https://hdl.handle.net/20.500.11984/5882

Ardiny, H., Witwicki, S., & Mondada, F. (2015). Are Autonomous Mobile Robots Able to Take Over Construction? A Review. International Journal of Robotics Theory and Applications, 4, 10-21. https://ijr.kntu.ac.ir/article_13385.html

Aria, M., & Cuccurullo, C. (2017). bibliometrix : An R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11(4), 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Asfour, T., Schill, J., Peters, H., Klas, C., Bücker, J., Sander, C., Schulz, S., Kargov, A., Werner, T., & Bartenbach, V. (2013). ARMAR-4: A 63 DOF torque controlled humanoid robot | IEEE Conference Publication | IEEE Xplore. 2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids). https://doi.org/10.1109/HUMANOIDS.2013.7030004

Askarpour, M., Rossi, M., & Tiryakiler, O. (2020). Co-Simulation of Human-Robot Collaboration: from Temporal Logic to 3D Simulation. Electronic Proceedings in Theoretical Computer Science, 319, 1-8. https://doi.org/10.4204/eptcs.319.1

Atlas, B. D. (2022). Atlas® and beyond: the world's most dynamic robots. https://bostondynamics.com/atlas/

Bänziger, T., Kunz, A., & Wegener, K. (2018). Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions. Journal of Intelligent Manufacturing, 31(7), 1635-1648. https://doi.org/10.1007/s10845-018-1411-1

Bedaka, A. K., & Lin, C.-Y. (2018). CAD-based robot path planning and simulation using OPEN CASCADE. Procedia Computer Science, 133, 779-785. https://doi.org/10.1016/j.procs.2018.07.119

Bjorck, J., Castañeda, F., Cherniadev, N., Da, X., Ding, R., Fan, L., Fang, Y., Fox, D., Hu, F., & Huang, S. (2025). Gr00t n1: An open foundation model for generalist humanoid robots. arXiv preprint arXiv:2503.14734. https://doi.org/10.48550/arXiv.2503.14734

Bock, T., Linner, T., Ikeda, W., Bock, T., Linner, T., & Ikeda, W. (2012). Exoskeleton and Humanoid Robotic Technology in Construction and Built Environment | IntechOpen. The Future of Humanoid Robots - Research and Applications. https://doi.org/10.5772/27694

Bossecker, E., Calepso, A. S., Kaiser, B., Verl, A., & Sedlmair, M. (2023). A Virtual Reality Simulator for Timber Fabrication Tasks Using Industrial Robotic Arms. Message Understanding Conference. https://doi.org/10.1145/3603555.3609316

Brosque, C., Galbally, E., Khatib, O., & Fischer, M. (2020). Human-Robot Collaboration in Construction: Opportunities and Challenges | IEEE Conference Publication | IEEE Xplore. 2020 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). https://doi.org/10.1109/HORA49412.2020.9152888

Buxbaum, H., Kleutges, M., & Sen, S. (2018). Full-Scope Simulation of Human-Robot Interaction in Manufacturing systems. 2018 Winter Simulation Conference (WSC). https://doi.org/10.1109/WSC.2018.8632246

Buxbaum, H., Sen, S., & Kremer, L. (2019). An Investigation into the Implication of Human-Robot Collaboration in the Health Care Sector. IFAC-PapersOnLine, 52(19), 217-222. https://doi.org/10.1016/j.ifacol.2019.12.100

Cao, L. (2024). Ai robots and humanoid ai: Review, perspectives and directions. arXiv preprint arXiv:2405.15775. https://doi.org/10.48550/arXiv.2405.15775

Čapek, K., & Kallinikov, I. (1940). Rossum's Universal Robots. Fr. Borový Prague, Czechoslovakia. https://www.playsfortheatre.com/assets/files/Rossums-UniversalRobots.pdf

Carra, G., Argiolas, A., Bellissima, A., Niccolini, M., Ragaglia, M., Carra, G., Argiolas, A., Bellissima, A., Niccolini, M., & Ragaglia, M. (2018). Robotics in the Construction Industry: State of the Art and Future Opportunities. International Symposium on Automation and Robotics in Construction (ISARC) Proceedings, 2018 Proceedings of the 35th ISARC, Berlin, Germany. https://doi.org/10.22260/ISARC2018/0121

Chen, C. (2016). CiteSpace: a practical guide for mapping scientific literature. Nova Science Publishers Hauppauge, NY, USA.

Cheng, J., Mu, Y., Li, L., Wang, M., Yue, C., Yang, W., Liu, C., & Dong, L. (2023). A Four-Capacitor Tactile Sensor Based on Bump Structure and Compensating Method to Reduce Inertial Interference for Robotic Tactile Sensing. IEEE Sensors Journal, 23(18), 21670-21678. https://doi.org/10.1109/jsen.2023.3291534

Chikwendu, O. C., Ezeanyim, O., & Igbokwe, N. C. (2023). Human-Robot Interaction Enhancement Through Ergonomics and Human Factors: Future Directions. International Journal of Engineering Research and Development, 19(6), 34-40. https://hal.science/hal-04348897v1

Chiriatti, G., Ciccarelli, M., Forlini, M., Franchini, M., Palmieri, G., Papetti, A., & Germani, M. (2022). Human-Centered Design of a Collaborative Robotic System for the Shoe-Polishing Process. Machines, 10(11). https://doi.org/10.3390/machines10111082

Chu, B., Kim, D., & Hong, D. (2008). Robotic automation technologies in construction: A review. International Journal of Precision Engineering and Manufacturing, 9(3), 85-91. https://koreascience.kr/article/JAKO200824556527779.page

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). Science mapping software tools: Review, analysis, and cooperative study among tools. Journal of the American Society for Information Science and Technology, 62(7), 1382-1402. https://doi.org/10.1002/asi.21525

Dario, P., Guglielmelli, E., & Laschi, C. (2001). Humanoids and personal robots: Design and experiments. Journal of robotic systems, 18(12), 673-690. https://doi.org/10.1002/rob.8106

Davila Delgado, J. M., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., & Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. Journal of Building Engineering, 26. https://doi.org/10.1016/j.jobe.2019.100868

Deniša, M., Ude, A., Simonič, M., Kaarlela, T., Pitkäaho, T., Pieskä, S., Arents, J., Judvaitis, J., Ozols, K., Raj, L., Czmerk, A., Dianatfar, M., Latokartano, J., Schmidt, P. A., Mauersberger, A., Singer, A., Arnarson, H., Shu, B., Dimosthenopoulos, D.,…Lanz, M. (2023). Technology Modules Providing Solutions for Agile Manufacturing. Machines, 11(9). https://doi.org/10.3390/machines11090877

Denny, J., Elyas, M., D'costa, S. A., & D'Souza, R. D. (2016). Humanoid robots–past, present and the future. European Journal of Advances in Engineering and Technology, 3(5), 8-15.

Dianatfar, M., Latokartano, J., & Lanz, M. (2020). Concept for virtual safety training system for human-robot collaboration. Procedia Manufacturing, 51, 54-60. https://doi.org/10.1016/j.promfg.2020.10.009

Diffler, M. A., Huber, F. L., Culbert, C., Ambrose, R. O., & Bluethmann, W. (2003). Human-robot control strategies for the NASA/DARPA Robonaut. IEEE Aerospace Conference. Proceedings. https://doi.org/10.1109/AERO.2003.1235578

Eaton, M. (2007). Evolutionary Humanoid Robotics: Past, Present and Future. In M. Lungarella, F. Iida, J. Bongard, & R. Pfeifer (Eds.), 50 Years of Artificial Intelligence: Essays Dedicated to the 50th Anniversary of Artificial Intelligence (pp. 42-52). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-77296-5_5

Elattar, S. (2008). Automation and robotics in construction: opportunities and challenges. Emirates journal for engineering research, 13(2), 21-26.

Eswaran, M., Gulivindala, A. K., Inkulu, A. K., & Raju Bahubalendruni, M. V. A. (2023). Augmented reality-based guidance in product assembly and maintenance/repair perspective: A state of the art review on challenges and opportunities. Expert Systems with Applications, 213. https://doi.org/10.1016/j.eswa.2022.118983

Etzi, R., Huang, S., Scurati, G. W., Lyu, S., Ferrise, F., Gallace, A., Gaggioli, A., Chirico, A., Carulli, M., & Bordegoni, M. (2019). Using Virtual Reality to Test Human-Robot Interaction During a Collaborative Task. Volume 1: 39th Computers and Information in Engineering Conference. https://doi.org/10.1115/DETC2019-97415

Everett, J. G., & Slocum, A. H. (1994). Automation and Robotics Opportunities: Construction versus Manufacturing. Journal of Construction Engineering and Management, 120(2), 443-452. https://doi.org/10.1061/(asce)0733-9364(1994)120:2(443)

Fareh, R., Khadraoui, S., Abdallah, M. Y., Baziyad, M., & Bettayeb, M. (2021). Active disturbance rejection control for robotic systems: A review. Mechatronics, 80. https://doi.org/10.1016/j.mechatronics.2021.102671

Fukuda, T., Dario, P., & Yang, G. Z. (2017). Humanoid robotics-History, current state of the art, and challenges. Sci Robot, 2(13). https://doi.org/10.1126/scirobotics.aar4043

Gallala, A., Kumar, A. A., Hichri, B., & Plapper, P. (2022). Digital Twin for Human-Robot Interactions by Means of Industry 4.0 Enabling Technologies. Sensors (Basel), 22(13). https://doi.org/10.3390/s22134950

Gonsalves, N. J. (2023). Understanding Underlying Risks and Socio-technical Challenges of Human-Wearable Robot Interaction in the Construction Industry. http://hdl.handle.net/10919/115667

Guizzo, E., & Ackerman, E. (2015). The hard lessons of DARPA's robotics challenge [News]. IEEE Spectrum, 52(8), 11-13. https://doi.org/10.1109/mspec.2015.7164385

Gupta, P., Tirth, V., & Srivastava, R. K. (2006). Futuristic Humanoid Robots: An Overview | IEEE Conference Publication | IEEE Xplore. First International Conference on Industrial and Information Systems. https://doi.org/10.1109/ICIIS.2006.365732

Gursch, H., Silva, N., Reiterer, B., Paletta, L., Bernauer, P. J., Fuchs, M., Veas, E., & Kern, R. (2018). Flexible Scheduling for Human Robot Collaboration in Intralogistics Teams. Message Understanding Conference. https://doi.org/10.18420/MUC2018-WS18-0528

Haddaway, N. R., Page, M. J., Pritchard, C. C., & McGuinness, L. A. (2022). PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis. Campbell Syst Rev, 18(2), e1230. https://doi.org/10.1002/cl2.1230

Hale, M. F., Buchanan, E., Winfield, A. F., Timmis, J., Hart, E., Eiben, A. E., Angus, M., Veenstra, F., Li, W., Woolley, R., De Carlo, M., & Tyrrell, A. M. (2019). The ARE Robot Fabricator: How to (Re)produce Robots that Can Evolve in the Real World. The 2019 Conference on Artificial Life. https://doi.org/10.1162/isal_a_00147

Han, I. X. (2023). Humans and Robots Improvise to Design-Fabricate in Virtual Reality | IEEE Conference Publication | IEEE Xplore. 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW). https://doi.org/10.1109/VRW58643.2023.00327

Hassija, V., Chamola, V., De, R., Das, S., Chakrabarti, A., Sangwoan, K. S., & Pandey, A. (2024). A Survey on Digital Twins: Enabling Technologies, Use Cases, Application, Open Issues and More. IEEE Journal of Selected Areas in Sensors. https://doi.org/10.1109/JSAS.2024.3523856

Hirose, M., & Ogawa, K. (2007). Honda humanoid robots development. Philos Trans A Math Phys Eng Sci, 365(1850), 11-19. https://doi.org/10.1098/rsta.2006.1917

Hodson, H. (2013). Robots to the rescue. New Scientist, 219(2934), 19-20. https://doi.org/10.1016/s0262-4079(13)62232-0

Huang, Z., Mao, C., Wang, J., & Sadick, A.-M. (2021). Understanding the key takeaway of construction robots towards construction automation. Engineering, Construction and Architectural Management, 29(9), 3664-3688. https://doi.org/10.1108/ecam-03-2021-0267

Ikuabe, M., Aigbavboa, C., & Kissi, E. (2023). Potential applications and benefits of humanoids in the construction industry: a South African perspective. International Journal of Building Pathology and Adaptation, 41(6), 254-268. https://doi.org/10.1108/ijbpa-04-2023-0042

Kamath, A., & Sharma, R. K. (2019). Robotics in construction: opportunities and challenges. International Journal of Recent Technology and Engineering, 8(2S11), 2227-2230. https://doi.org/10.35940/ijrte.B1242.0982S1119

Kaneko, K., Kaminaga, H., Sakaguchi, T., Kajita, S., Morisawa, M., Kumagai, I., & Kanehiro, F. (2019). Humanoid Robot HRP-5P: An Electrically Actuated Humanoid Robot With High-Power and Wide-Range Joints. IEEE Robotics and Automation Letters, 4(2), 1431-1438. https://doi.org/10.1109/lra.2019.2896465

Kastrin, A., & Hristovski, D. (2021). Scientometric analysis and knowledge mapping of literature-based discovery (1986–2020). Scientometrics, 126(2), 1415-1451. https://doi.org/10.1007/s11192-020-03811-z

Kim, S., Anthis, J. R., & Sebo, S. (2024). A Taxonomy of Robot Autonomy for Human-Robot Interaction Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction, Boulder, CO, USA. https://doi.org/10.1145/3610977.3634993

Kuts, V., Otto, T., Tähemaa, T., Bukhari, K., & Pataraia, T. (2019). Adaptive Industrial Robots Using Machine Vision. Volume 2: Advanced Manufacturing. https://doi.org/10.1115/IMECE2018-86720

Law, K. K., Chang, S., & Siu, M.-F. F. (2022). Factors Influencing Adoption of Construction Robotics in Hong Kong's Industry: A Multistakeholder Perspective. Journal of Management in Engineering, 38(2). https://doi.org/10.1061/(asce)me.1943-5479.0001011

Leite, F., Cho, Y., Behzadan, A. H., Lee, S., Choe, S., Fang, Y., Akhavian, R., & Hwang, S. (2016). Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry. Journal of Computing in Civil Engineering, 30(6). https://doi.org/10.1061/(asce)cp.1943-5487.0000604

Lutz, V., de Matteïs, L., Batto, V., & Mansard, N. (2025). Control of Humanoid Robots with Parallel Mechanisms using Kinematic Actuation Models. https://doi.org/10.48550/arXiv.2503.22459

Madl, A. K., Donovan, E. P., Gaffney, S. H., McKinley, M. A., Moody, E. C., Henshaw, J. L., & Paustenbach, D. J. (2008). State-of-the-science review of the occupational health hazards of crystalline silica in abrasive blasting operations and related requirements for respiratory protection. J Toxicol Environ Health B Crit Rev, 11(7), 548-608. https://doi.org/10.1080/10937400801909135

Mahbub, R. (2008). An investigation into the barriers to the implementation of automation and robotics technologies in the construction industry https://eprints.qut.edu.au/26377/

Malik, A. A., Masood, T., & Brem, A. (2023). Intelligent humanoids in manufacturing to address worker shortage and skill gaps: Case of Tesla Optimus. https://doi.org/10.48550/arXiv.2304.04949

Mattern, D., López, F. M., Ernst, M. R., Aubret, A., & Triesch, J. (2022). MIMo: A Multi-Modal Infant Model for Studying Cognitive Development in Humans and AIs | IEEE Conference Publication | IEEE Xplore. https://doi.org/10.1109/ICDL53763.2022.9962192

Metta, G., Natale, L., Nori, F., Sandini, G., Vernon, D., Fadiga, L., von Hofsten, C., Rosander, K., Lopes, M., Santos-Victor, J., Bernardino, A., & Montesano, L. (2010). The iCub humanoid robot: an open-systems platform for research in cognitive development. Neural Netw, 23(8-9), 1125-1134. https://doi.org/10.1016/j.neunet.2010.08.010

Mutis, I., Dulanto, P., & Hussain, S. M. (2024). Challenges of Simulated Humanoid Robots for Construction Tasks in the Immersive Environment Proceedings of the 3rd Future of Construction Workshop at the International Conference on Robotics and Automation (ICRA 2024), https://doi.org/10.22260/icra2024/0008

Nazir, T. A., Lebrun, B., & Li, B. (2023). Improving the acceptability of social robots: Make them look different from humans. PLOS ONE, 18(11), e0287507. https://doi.org/10.1371/journal.pone.0287507

Nelson, G., Saunders, A., & Playter, R. (2019). The PETMAN and Atlas Robots at Boston Dynamics. Humanoid Robotics: A Reference. https://doi.org/10.1007/978-94-007-6046-2_15

Niazi, M. A. (2016). Review of “CiteSpace: A practical guide for mapping scientific literature” by Chaomei Chen. https://doi.org/10.1186/s40294-016-0036-5

Oke, A. E., Aliu, J., Fadamiro, P., Jamir Singh, P. S., Samsurijan, M. S., & Yahaya, M. (2024). Robotics and automation for sustainable construction: microscoping the barriers to implementation. Smart and Sustainable Built Environment, 13(3), 625-643. https://doi.org/10.1108/SASBE-12-2022-0275

Onnasch, L., & Roesler, E. (2020). A Taxonomy to Structure and Analyze Human–Robot Interaction. International Journal of Social Robotics, 13(4), 833-849. https://doi.org/10.1007/s12369-020-00666-5

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hrobjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S.,…Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

Pandey, A. K., & Gelin, R. (2018). A Mass-Produced Sociable Humanoid Robot: Pepper: The First Machine of Its Kind. IEEE Robotics & Automation Magazine, 25(3), 40-48. https://doi.org/10.1109/mra.2018.2833157

Pons, J. L. (2008). Wearable robots: biomechatronic exoskeletons. John Wiley & Sons. https://doi.org/10.1002/9780470987667

Pradhananga, P., ElZomor, M., & Santi Kasabdji, G. (2021). Identifying the Challenges to Adopting Robotics in the US Construction Industry. Journal of Construction Engineering and Management, 147(5). https://doi.org/10.1061/(asce)co.1943-7862.0002007

Radnoff, D. L., & Kutz, M. K. (2014). Exposure to crystalline silica in abrasive blasting operations where silica and non-silica abrasives are used. Ann Occup Hyg, 58(1), 19-27. https://doi.org/10.1093/annhyg/met065

Reilly, T., O’Rourke, J. K., Steudler, D., Piovesan, D., & Bortoletto, R. (2016). Locomotive Underactuated Implement Guided via Elastic Elements (L.U.I.G.E.E): A Preliminary Design. Volume 3: Biomedical and Biotechnology Engineering. https://doi.org/10.1115/IMECE2015-50567

Riccio, T. (2021). Sophia Robot: An Emergent Ethnography. TDR: The Drama Review, 65(3), 42-77. https://doi.org/10.1017/S1054204321000319

Rodriguez-Guerra, D., Sorrosal, G., Cabanes, I., & Calleja, C. (2021). Human-Robot Interaction Review: Challenges and Solutions for Modern Industrial Environments. IEEE Access, 9, 108557-108578. https://doi.org/10.1109/access.2021.3099287

Saeedvand, S., Jafari, M., Aghdasi, H. S., & Baltes, J. (2019). A comprehensive survey on humanoid robot development. The Knowledge Engineering Review, 34, e20. https://doi.org/10.1017/S0269888919000158

Schoffmann, C., Erickson, Z., & Zangl, H. (2022). CapSense: A Real-Time Capacitive Sensor Simulation Framework for Physical Human-Robot Interaction. IEEE Robotics and Automation Letters, 7(4), 9929-9936. https://doi.org/10.1109/lra.2022.3191942

Shen, Y.-T., & Hsu, J.-S. (2023). The Development of Mix-Reality Interface and Synchronous Robot Fabrica. Lecture Notes in Computer Science. https://doi.org/10.1007/978-3-031-35634-6_26

Su, Y. (2023). Artificial Intelligence: The Significance of Tesla Bot. Highlights in Science, Engineering and Technology, 39, 1351-1355. https://doi.org/10.54097/hset.v39i.6767

Taher, G. (2021). Industrial Revolution 4.0 in the construction industry: Challenges and opportunities. Management Studies and Economic Systems, 6(3/4), 109-127. https://doi.org/10.12816/0060000

Takanishi, A. (2019). Historical perspective of humanoid robot research in Asia. In Humanoid Robotics: A Reference (pp. 35-52). Springer.

Tong, Y., Liu, H., & Zhang, Z. (2024). Advancements in Humanoid Robots: A Comprehensive Review and Future Prospects. IEEE/CAA Journal of Automatica Sinica, 11(2), 301-328. https://doi.org/10.1109/jas.2023.124140

Unbehauen, H. D. (2009). Control Systems, Robotics and Automation–Volume XXI: Elements of Automation. EOLSS Publications.

Unitree Robotics. (2024). Unitree G1: Humanoid Agent AI Avatar. https://www.unitree.com/g1

Vaduva-Sahhanoglu, A.-M., Calbureanu-Popescu, M. X., & Smid, S. (2016). Automated and robotic construction-a solution for the social challenges of the construction sector. Revista de stiinte politice(50), 211. https://www.ceeol.com/search/article-detail?id=730097

van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523-538. https://doi.org/10.1007/s11192-009-0146-3

Vukobratovic, M., Potkonjak, V., & Tzafestas, S. (2004). Human and Humanoid Dynamics. Journal of Intelligent and Robotic Systems, 41(1), 65-84. https://doi.org/10.1023/B:JINT.0000049169.28413.df

Wang, S., Mao, Z., Zeng, C., Gong, H., Li, S., & Chen, B. (2010, 18-20 June 2010). A new method of virtual reality based on Unity3D. 2010 18th International Conference on Geoinformatics,

Wuzella, R. (2022). Instructing Tacit Knowledge: Epistemologies of Sensory-Based Robotic Systems. Technology and Language, 7(2). https://doi.org/10.48417/technolang.2022.02.03

Xu, X., Holgate, T., Coban, P., & García de Soto, B. (2022). Implementation of a robotic system for overhead drilling operations: a case study of the Jaibot in the UAE. International Journal of Automation & Digital Transformation, 1(1), 37-58. https://doi.org/10.22260/ISARC2021/0089

Yang, X., Sousa Calepso, A., Amtsberg, F., Menges, A., & Sedlmair, M. (2023). Usability Evaluation of an Augmented Reality System for Collaborative Fabrication between Multiple Humans and Industrial Robots. https://doi.org/10.1145/3607822.3614528

Yoo, J. K., Lee, B. J., & Kim, J. H. (2009). Recent progress and development of the humanoid robot HanSaRam. Robotics and Autonomous Systems, 57(10), 973-981. https://doi.org/10.1016/j.robot.2009.07.012

Zahabi, M., & Abdul Razak, A. M. (2020). Adaptive virtual reality-based training: a systematic literature review and framework. Virtual Reality, 24(4), 725-752. https://doi.org/10.1007/s10055-020-00434-w

Zhu, W., Fan, X., & Zhang, Y. (2019). Applications and research trends of digital human models in the manufacturing industry. Virtual Reality & Intelligent Hardware, 1(6), 558-579. https://doi.org/10.1016/j.vrih.2019.09.005

Zupic, I., & Čater, T. (2014). Bibliometric Methods in Management and Organization. Organizational Research Methods, 18(3), 429-472. https://doi.org/10.1177/1094428114562629