CHAPTER 21

APPLICATION OF EXOSKELETONS FOR OCCUPATIONAL SAFETY AND HEALTH MANAGEMENT IN CONSTRUCTION: A SYSTEMATIC REVIEW

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ABSTRACT
The construction industry is a high-risk industry due to its poor record of injuries and deaths globally. Recently, exoskeletons as part of a suite of industry 4.0 have emerged as a potential effective technological approach for addressing the unsatisfactory construction occupational safety and health (OSH) performance. To gain a comprehensive view of the application of exoskeletons in addressing the OSH issues in the construction industry, a systematic review of the extant literature on exoskeletons for construction OSH management is conducted. The review reveals that OSH areas/topics covered by exoskeleton-related studies include risk assessment and control, and design for safety. Furthermore, exoskeletons have been used to address manual handling hazards, which induce work-related musculoskeletal disorders. These findings could help address the minimal focus of researchers and industry practitioners on the use of exoskeletons for construction OSH management. The various challenges associated with the application of exoskeletons for construction OSH management, which include the discomfort experienced by the users of exoskeletons and the difficulty in using exoskeletons with other PPEs such as fall-arrest harnesses, are also highlighted. Recommendations for future research include investigating ways to improve the design of the exoskeletons so that wearers will feel far less discomfort.

INTRODUCTION

The construction sector is one of the most dangerous industrial sectors to work in. For instance, over 1,000 deaths were recorded in the industry in the United States of America in 2020 (Bureau of Labor Statistic, 2021). Globally, the industry accounts for over 100,000 deaths every year (ILO, 2015). The poor occupational safety and health (OSH) status of the construction industry therefore requires urgent intervention. This study explores the application of industry 4.0 technologies for addressing the OSH challenges in the construction industry with particular emphasis on the role of exoskeletons.

Industry 4.0 technologies can be defined as the automation of manufacturing processes and technologies with highly interconnected components such as sensors, cyber-physical systems and the Internet of Things (IoT) components (Nigam and Talcott, 2022). Industry 4.0 technologies include robotics such as exoskeletons, big data and analytics, immersive technologies, additive manufacturing, cloud computing, cyber-security and the internet of things (Rüßmann *et al.*, 2015). The construction industry is increasingly integrating industry 4.0 technologies to modify its workflows, but it has been very slow in utilising these technologies for construction safety purposes (Afzal *et al*., 2021).

Construction-related activities usually involve the intense movement of workers' body parts in awkward positions, making the workers highly prone to instantaneous and long-term injuries (Chen *et al.*, 2017). Work-related musculoskeletal disorders (WMSDs) cause fatigue and pain in workers which could result in the non-presence of the workers at the jobsite (de Oliveira Sato and Cote Gil Coury, 2009). Manual handling, lifting or carrying is a common cause of WMSDs (Health and Safety Executive, 2020). It is stated that manual handling causes more than one-third of occupational injuries in the workplaces including the construction industry (Health and Safety Executive, 2022) . Ogunseiju *et al.* (2021) defined manual handling as the human efforts used in transporting, pushing, pulling and the physical lifting of construction equipment and materials. It has been determined that manual lifting is a major cause of back WMSDs (Zurada, 2012). In construction, warehousing and agricultural sectors, about 75% of back injuries occur when lifting heavy objects (Pistolesi and Lazzerini, 2020). WMSDs is known to be very costly to national economies, employer's economic productivity and it causes personal and family suffering (Hondzinski *et al.*, 2019). It is one of the top causes of absenteeism and early retirement of workers as they become incapable of carrying out their daily activities at work (Da Costa and Vieira, 2010; O'Sullivan *et al.*, 2015). Equipment such as forklift trucks and overhead cranes can be used to transfer heavy objects on site, but they have limitations regarding spaces for installations and the ranges of movements (Yu *et al.*, 2015). Yu *et al.* (2015) recommend exoskeletons for handling heavy loads to curb the risk of accidents and reduce the tendency of workers to get WMSDs on jobsites. Exoskeletons are rapidly growing in the consumer market and it has great potential use for the reduction of physical demands and fatigue in order to prevent WMSDs (Kazerooni, 2008; de Looze *et al.*, 2016; Kim *et al.*, 2019). Exoskeletons could thus be useful in protecting workers from the risks of WMSDs and other occupational diseases (Ren *et al.*, 2021). This study therefore focuses on the role of exoskeletons in OSH management in the construction industry.

The central research questions this study aims to address are:

1. What is the current state of research on the application of exoskeletons for construction OSH management? In particular, what construction OSH areas/topics, hazard types, and conditions are addressed by exoskeletons in academic literature?
2. What are the challenges/limitations and future research directions regarding the application of exoskeletons for construction OSH management?

BACKGROUND

Robotics is the integration of mechanical, electrical and software engineering developed for the execution of dangerous, demanding or dirty activities (Ruggiero and Salvo, 2016). Automation can be referred to as the use of digital machines for the execution of activities (Oke *et al.*, 2017). Automation of activities with robots is becoming more rampant in the present day environment as robots are used for the execution of tasks in factories, homes and offices (Amediya, 2016). Various industries, including the construction industry are looking for effective methods for the automation of repetitive, time-consuming and dangerous activities in order to improve the OSH performance and also enhance the efficiency of workers (Kumar *et al.*, 2021). Robots have increasingly being applied in various personal and professional services such as medical, construction, demolition, vacuum-cleaning, education and laboratory (Sirinterlikci *et al.*, 2012). Furthermore, field and mobile robots are usually used in mining, agriculture, hazardous area repairs, search and rescue and many more (Sirinterlikci *et al.*, 2012). For instance, in the construction industry, the mixing of concrete is automated with the use of robots as they are used for the mixing of concrete, laying of cement, polishing of floors and the removal of surface water and this helps in the removal of human errors in these activities (Kumar *et al.*, 2021). The types of robots, the descriptions and examples of these robots are as shown in Table 21.1.

Table 21.1: Types of robots, the definitions and examples of the types of robots (Robotics, 2022)

Types of Robots	**Descriptions**	**Examples**
Pre-programmed robots	These are robots that are programmed to carry out simple, monotonous activities in a controlled environment.	Mechanical arm on an automotive assembly line
Humanoid robots	These are robots that sometimes have human looks and facial expressions and are used to perform human-like activities such as jumping and carrying objects.	Hanson Robotics' Sophia
Autonomous robots	These are robots developed with the use of sensors to carry out activities in an open environment without human intervention.	Roomba vacuum cleaner
Teleoperated robots	These are robots that are semi-autonomous as they are human controlled from a distance through wireless network and they are designed to work in extreme weather conditions.	Drones
Augmenting robots	These are robots that are designed to either enhance the capabilities or to replace the capabilities that might have been lost by a human.	Exoskeletons

Robots can also be used to enhance the OSH performance in the construction industry. However, the full automation of tasks is not always feasible especially for continuously varying tasks (de Looze *et al.*, 2016). Workers are therefore still exposed to activities such as manual handling which makes them prone to WMSDs but this can be addressed with the use of exoskeletons (de Looze *et al.*, 2016). Exoskeletons could be very useful especially for tasks that constantly change and the automation of these tasks is not feasible (Bosch *et al.*, 2016). Furthermore, it has been reported by Viteckova *et al.* (2013) that efforts have been made to combine robot and the human body into a single system so that human being who contributes in the form of intelligence to tasks can benefit from the performance, precision and power of robotic systems.

Exoskeletons, which could be active or passive, are wearable robotic assistive devices used to augment the mechanical power in the human body and thereby minimising the biomechanical load on the human body (Huysamen *et al.*, 2018). The innovative ergonomic interventions to the physical load on human body parts have made exoskeletons, a subset of assistive devices increasingly becoming popular. They are designed to either augment human strength or to caution the wearers about risky postures (Ogunseiju *et al.*, 2021). Exoskeletons can be likened to the shell of a crab which acts as a shield to the body, a waterproof wall against desiccation, a surface for the connection of muscles, and a sensory interface within the surroundings (Gopura *et al.*, 2011). This describes how exoskeletons can be useful for the protection of its wearers. Moreover, the origin of exoskeletons can be traced to the innovation of a pocket watch as a wearable technology in the 16^{th} century which later evolved into the development of an exoskeleton which consisted of long springs attached to each human leg and compressed bags for storing energy from the spring action, developed to facilitate walking, running and jumping (Howard *et al.*, 2020). Consequently, in 1890, Nichola Yagn, a Russian inventor, obtained a patent for the exoskeleton which was developed to augment the ability of Russian soldiers to run (Howard *et al.*, 2020). Exoskeletons could therefore be useful for construction OSH management especially in augmenting worker ability in performing tasks as it has also been revealed that exoskeletons which could contain pneumatic, electric or hydraulic actuators can be used for human locomotion assistance, human strength augmentation and gait rehabilitation (Alqahtani *et al.*, 2021).

Active exoskeletons use actuators that are operated by electric motors or hydraulics to augment human strength as they work while passive exoskeletons which are less expensive are unpowered systems that make use of springs and dampers to store the energy generated by the movement of the wearer and discharge such energies effectively (Ogunseiju *et al.*, 2021). Active exoskeletons could, however, have its drawbacks as Kazerooni (2008) revealed that some exoskeletons could depend on tether and external power supply to meet their high power consumption rate and this could adversely affect the free movement of the wearers of such exoskeletons due to the tether. In addition, some well-known active exoskeletons such as muscle suit are very expensive for workers (RoboticsBiz, 2021). This may explain why passive exoskeletons are relatively common in the market place than active exoskeletons (Huysamen *et al.*, 2018). It has been seen that passive exoskeletons significantly lessens the muscle activity of the lower back but fatigue of the arm muscles during manual handling is ignored (RoboticsBiz, 2021). Ogunseiju *et al.* (2021) provided a list of different exoskeletons including Laevo exoskeletons designed to support the back; EksoVest exoskeletons which support the abdomen and back; Paexo exoskeletons which support the shoulder, arm and back; ShoulderX exoskeletons which support the arm; and many more. These exoskeletons have been applied in various industrial sectors such as HULC developed by

Lockheed, and XOS series developed by Raytheon for military application, and Rewalk developed by Rewalk Robotics for healthcare application (Yu *et al.*, 2015). A study by Kim *et al.* (2022) showed that exoskeletons can lessen the fatigue and strain in the shoulders of workers with positive effects on job performance in the automotive industry. There is, however, the lack of a comprehensive study on the role of exoskeletons in addressing OSH challenges in the construction industry.

METHODOLOGY

Due to the poor OSH performance of the construction industry, it has become necessary for effective interventions to improve the OSH status of the industry and a potential effective intervention involves the application of industry 4.0 technologies. It has, however, been noted that there is a lack of review that offers a comprehensive view of the role of exoskeletons in OSH management in the construction industry. To address this gap, this study conducted a systematic literature review (SLR) on the application of exoskeletons for addressing the poor OSH status in the construction sector.

Review Approach

A SLR was conducted based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) to obtain articles related to the application of exoskeletons for construction OSH management. This study reviewed related journal articles since they are peer-reviewed and also provide a more extensive and higher quality information when compared to other types of publications (Farghaly *et al.*, 2021; Hou *et al.*, 2021). The articles were obtained from Scopus and Web of Science (WoS) databases search as these databases have extensive coverage of scientific literature. Scopus is also arguably the largest database of peer-reviewed articles, covering over 37,000 titles from approximately 11,500 publishers of which over 34,000 represent peer-reviewed journals that are domiciled within high-impact and trending research disciplines. The search was conducted in March 2022, under an unrestricted timeframe. The keywords used for the search were divided into three fields: the first field focused on industry 4.0 technology, especially exoskeletons; the second field focused on the construction industry; and the third field focused on OSH. Figure 21.1 shows a systematic flowchart which displays the SLR process adopted in this study.

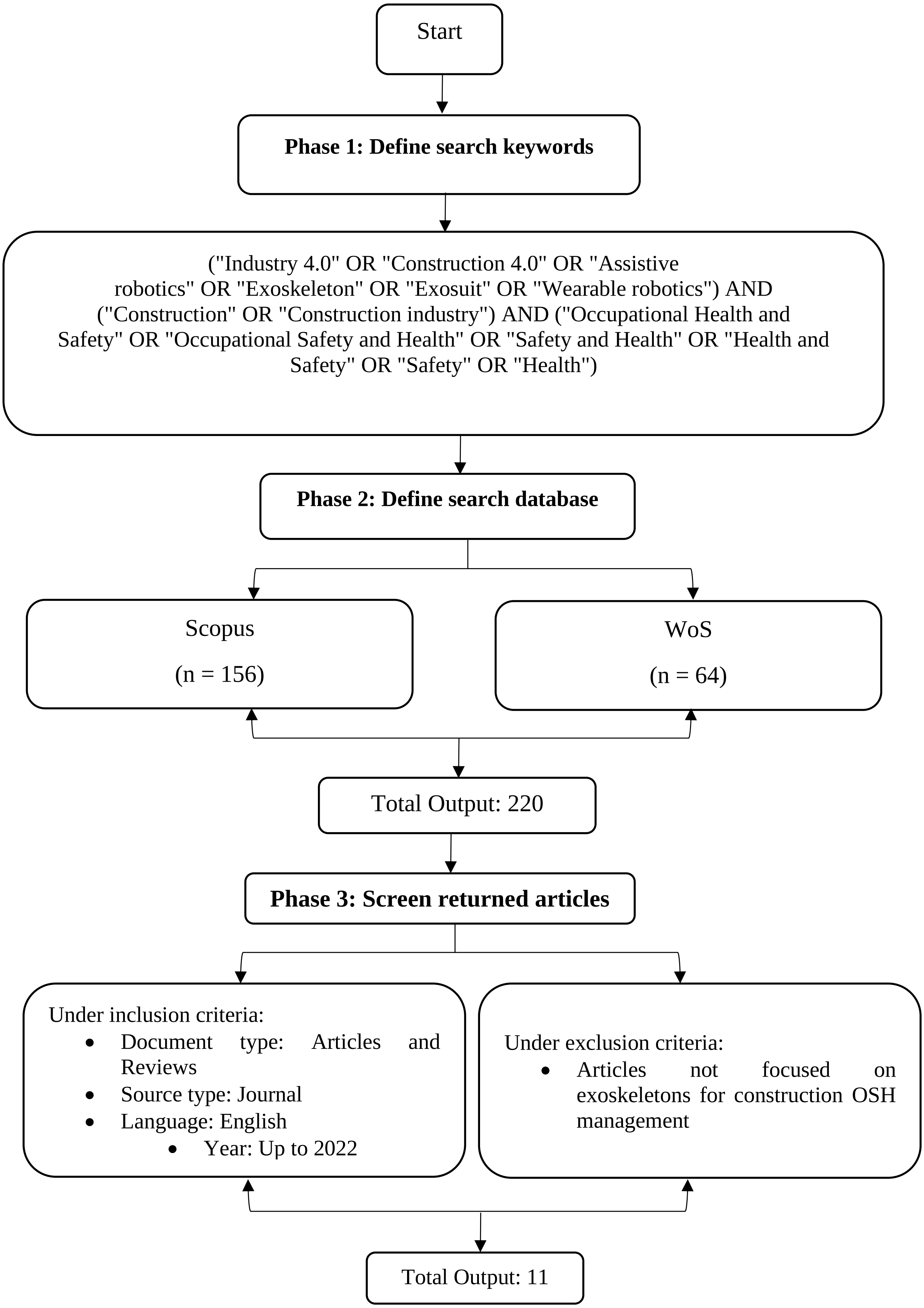

Figure 21.1: Systematic literature review flowchart

The set of search strings applied to verify the title, abstract and keyword of the papers collected from Scopus database is as follow:

> *(TITLE-ABS-KEY ("Industry 4.0" OR "Construction 4.0" OR "Assistive robotics" OR "Exoskeleton" OR "Exosuit" OR "Wearable robotics") AND TITLE-ABS-KEY ("Construction" OR "Construction industry") AND TITLE-ABS-KEY ("Occupational Health and Safety" OR "Occupational Safety and Health" OR "Safety and Health" OR "Health and Safety" OR "Safety" OR "Health"))*

The set of search strings applied to verify the title, abstract and keyword of the papers collected from Web of Science (WoS) database is as follow:

> *((TI=("Industry 4.0" OR "Construction 4.0" OR "Assistive robotics" OR "Exoskeleton" OR "Exosuit" OR "Wearable robotics") AND TI=("Construction" OR "Construction industry") AND TI=("Occupational Health and Safety" OR "Occupational Safety and Health" OR "Safety and Health" OR "Health and Safety" OR "Safety" OR "Health")) OR (AB=("Industry 4.0" OR "Construction 4.0" OR "Assistive robotics" OR "Exoskeleton" OR "Exosuit" OR "Wearable robotics") AND AB=("Construction" OR "Construction industry") AND AB=("Occupational Health and Safety" OR "Occupational Safety and Health" OR "Safety and Health" OR "Health and Safety" OR "Safety" OR "Health")) OR (AK=("Industry 4.0" OR "Construction 4.0" OR "Assistive robotics" OR "Exoskeleton" OR "Exosuit" OR "Wearable robotics") AND AK=("Construction" OR "Construction industry") AND AK=("Occupational Health and Safety" OR "Occupational Safety and Health" OR "Safety and Health" OR "Health and Safety" OR "Safety" OR "Health")))*

The initial search retrieved 156 articles from Scopus and 64 articles from WoS databases, making a total of 220 articles. The search strings were then limited to journal publications because they provide more comprehensive information on the field of study. The number of journal publications written in English language that was collected from Scopus and WoS databases were 66 articles and 41 articles respectively, making it a total of 107 articles. An example of the many rejected articles due to lack of relevance of its contents is the article titled ‘Design, Development, and Validation of an Augmented Reality-Enabled Production Strategy Process’ by Nassereddine *et al.* (2022). The contents of this article were on the current state of application of production strategy process (PSP), which also identified its challenges and examined how augmented reality can be integrated with PSP (Nassereddine *et al.*, 2022). Eventually, the 107 articles were screened by the contents of the abstract and titles. This resulted in 11 articles considered relevant to the scope of this study as depicted in Figure 21.1.

RESULTS AND DISCUSSIONS

This section presents the results and discussions of the SLR of the selected nine articles. To achieve an effective analysis of these articles, the study identified the location of studies, research methods used by the studies, the main outcomes of the studies, the different construction OSH areas covered /addressed by application of exoskeletons, the different types of OSH hazards and conditions, and the challenges associated with the applications of exoskeletons for construction OSH management. The SLR further identified future research directions.

Frequency Analysis

The frequency analysis of the articles was undertaken to reveal trends and patterns in the distribution of the articles based on the year of publication, location of study, research method, and title of journal.

Distribution of articles by year

Figure 21.2 shows the number of articles for every year and it shows that studies about exoskeletons in construction commenced in 2015 with a study conducted on the development of a standalone powered exoskeleton robots to augment the human strength in the lower back, hip joints and waist which are vulnerable body parts during manual handling of heavy objects. The commencement of the studies on exoskeletons for construction OSH management in 2015 could have been stimulated by the significant increase in the scientific production of articles on industry 4.0 around the early 2010s (Petrillo *et al.*, 2018). It has been observed that no study was published on the use of exoskeletons for addressing construction OSH challenges in the year 2016 up to 2018. Furthermore, two studies were published in 2019, one of which compared the design of three passive exoskeletons in a mock drilling activity (Alabdulkarim *et al.*, 2019). After 2019, there was a significant increase in the number of publications. An example of the studies published in 2020 is 'Assessing the Risk of Low Back Pain and Injury via Inertial and Barometric Sensors' in Pistolesi and Lazzerini (2020) presented an artificial intelligence (AI) based system that utilises wearable sensors for the assessment of the safety of workers while lifting heavy loads. Additional two articles were published in 2021. Amongst them, Ren *et al.* (2021) proposed a physical human-robot interactive (pHRI) controller designed for construction activities and integrates a trajectory-based musculoskeletal model with iterative control algorithms with the gait dynamic modelled as a spring damping to reduce the trajectory tracking error between the lower limb exoskeletons and the human lower limbs. Overall, the distribution of articles by year shows an undulating trend, which highlights a potential for growth in research in the domain of exoskeleton application in construction. The number of articles published has, however, been minimal and with the potential benefits that exoskeletons provide for construction OSH management, it is highly recommended that more research studies should be conducted on exoskeletons for construction OSH management. Consequently, an increase in studies on exoskeletons for construction OSH management could result in an increase in the use of exoskeletons by construction workers thereby improving the poor OSH performances in the construction industry.

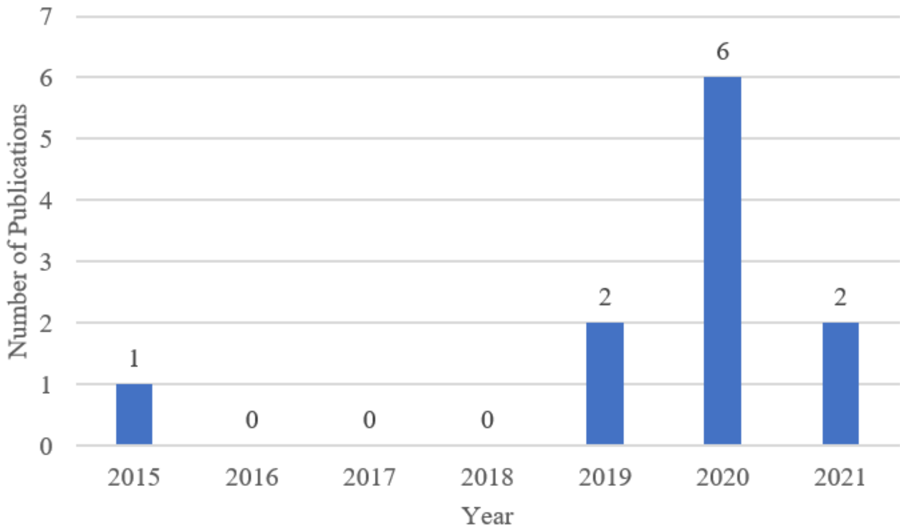

Figure 21.2: Distribution of articles by year

Distribution of articles by location of study

Figure 21.3 shows the distribution of articles by location of study. The figure indicates that studies have been conducted in nine countries since 2015 which are China (including Hong Kong), South Korea, Saudi Arabia, Italy, Australia, United Kingdom (UK), Canada, South Africa and the United States of America (USA). This is, however, not surprising as these countries are considered to be among the most digitally innovative countries globally (Martínez-Aires *et al.*, 2018; Akinlolu *et al.*, 2020; Institute of Management, 2021). Figure 21.3 also shows a concentration of studies in developed countries (i.e. high-income countries). Given that, poor OSH performance in construction is more acute in developing countries (i.e. low to middle-income countries) (Manu *et al.*, 2019), it would be useful for research attention to also be directed to these countries.

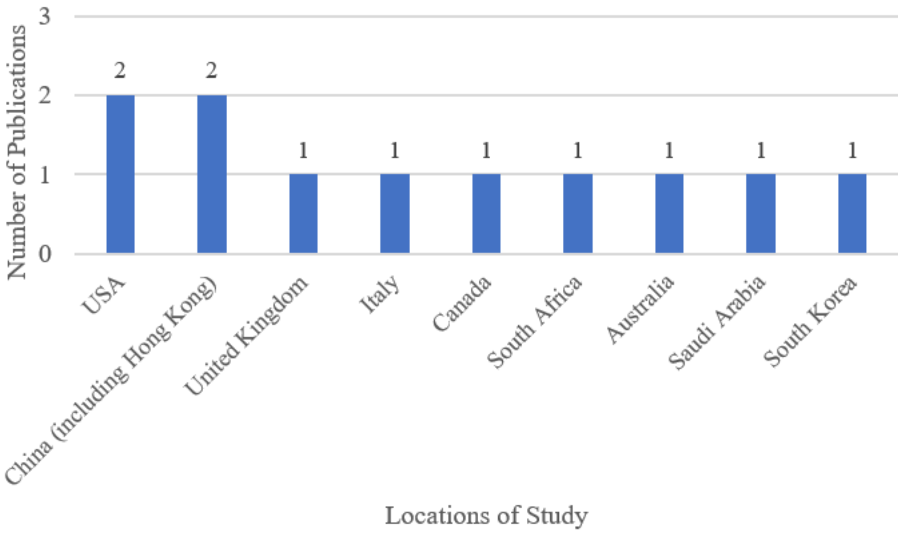

Figure 21.3: Distribution of Publications per Location of Study

The studies conducted in South Korea and Saudi Arabia presented different exoskeletons prototypes for lifting and drilling. The articles analysed the performance of the prototypes and evaluated their benefits and disadvantages for the OSH of the workers using them (Yu *et al.*, 2015; Alabdulkarim *et al*, 2019). The study by Meo *et al.* (2013) revealed that a large proportion of construction workers in Saudi Arabia complained of WMSDs, with construction workers who have worked for more than 6 years having higher symptoms. The study by Alabdulkarim *et al.* (2019) identified a shoulder-focused exoskeleton as effective for reducing physical demands on the body especially at the upper extremity and this could be used to address the WMSDs symptoms experienced by workers in Saudi Arabia and the construction industry globally. One of the studies conducted in the USA examined the potential of a postural-assist exoskeleton for manual handling tasks and it was discovered that there was a reduction in the physical demands of construction work on the wearers of the exoskeleton (Ogunseiju *et al.,* 2021). A study by Wang *et al.* (2017) reveals that the rate of WMSDs in construction workers almost doubled between 1992 and 2014 in the USA especially amongst workers aged 55 to 64 years. Wang *et al.* (2017) concluded that there was an urgent need to reduce overexertion at construction sites especially for workers that are prone to WMSDs. This implies that the study by Ogunseiju *et al.* (2021) could be a possible solution to the cause of WMSDs on construction sites in the USA and even in the construction industry globally.

Distribution of articles by research method

Figure 21.4 shows the distribution of articles by method of research applied. The figure indicates that different research methods have been adopted to further understand the effects of exoskeletons on construction OSH management. An example of such research methods is the experimental methods which were used in the literature.

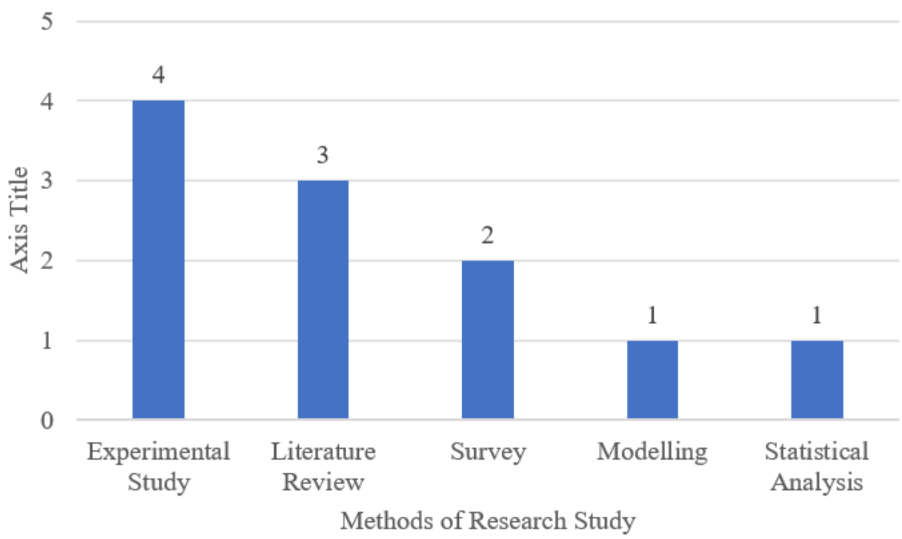

Figure 21.4: Distribution of Publications by Research Methods

Alabdulkarim *et al.* (2019) and Yu *et al.* (2015) used experiments to collect data from exoskeletons prototypes and assess their functionality. Another research method, observed in literature is systematic review of literature which did not explicitly explore exoskeletons, but touch on construction robotics as part of application of Industry 4.0 technologies in construction safety risk management (Darko *et al.*, 2020; Perrier *et al.*, 2020). The study conducted by Edwards *et al.* (2019) used modelling, interviews and experimental methods to study the effect of exposure to vibration in the arms and hands. Lastly, a survey was used as a research method to investigate the industry requirements and assessments of collaborative robot (CoBot) acceptances, and to explore the motion capture and tracking systems for a collaborative framework between human and robot co-workers (Reinhardt *et al.*, 2020). Overall, the distribution of articles by research method shows that there are more experimental studies in the area. Such quantitative studies are necessary in order to establish empirically the impact of exoskeleton on workers' safety, health as well as productivity. It is based on such quantitative evidence that organisation can formulate a case for investment into exoskeleton adoption.

Distribution of articles by journal titles

Out of the eleven relevant articles collected from the Scopus and WoS databases, two were published in the same journal. These are the works by Ogunseiju *et al.* (2021) and Edwards *et al.* (2019) in the 'Engineering, Construction and Architectural Management' journal. The remaining seven articles were published in different journals. For example, the 'International Journal of Architectural Computing' had a publication from Reinhardt *et al.* (2020) which explored the relationship between robot technology with a range of human trades within the construction industry such as painters, plasterers, bricklayers, carpenters, etc. Another study published in 'Applied Ergonomics' journal compared the design of three passive exoskeletons in a mock drilling task under three precision requirements levels (Alabdulkarim *et al.*, 2019). 'Computers in Industry' (Darko *et al.*, 2020), 'Journal of Information Technology in Construction' (Perrier *et al.*, 2020), 'IEEE Transactions on Industrial Informatics' (Pistolesi and Lazzerini, 2020), 'ISIJ International' (Yu *et al.*, 2015), 'Computer-aided Civil and Infrastructure Engineering Journal' (Ren *et al.*, 2021), IISE Transactions on Occupational Ergonomics & Human Factors (Kim *et al.*, 2019) and International Journal of Construction Management (Akinlolu *et al.*, 2020) are the remaining seven journals. Overall, the above commentary can serve as a signpost to guide researchers in determining suitable outlets for disseminating their study in the domain of exoskeleton application for construction OSH management.

State of Application of Exoskeletons to Construction OSH Management

The highly diverse nature of workers with different skill levels and safety cultures in the construction industry leads to numerous complex and high-risk activities. Although, the conventional OSH management regimes such as toolbox talks and wearing of personal protective equipment (PPEs) are deep-rooted at construction sites, their effectiveness has, however, been limited. Due to this, it has become necessary to explore the application of emerging technologies, such as exoskeletons, for the improvement of construction OSH management.

Occupational safety and health areas addressed by exoskeletons

The OSH areas/topics covered by exoskeletons as observed in literature are risk assessment and control, and design for safety. These are further discussed below.

Risk assessment and control

Risk management is a planned and structured process used to identify, manage, and control risks (Srinivas, 2019). The process of identifying the risks involved in the handling of heavy object and managing such risks with exoskeletons was adopted by Yu *et al.* (2015) as a novel stand-alone powered exoskeleton robot was developed for manual handling of heavy objects. This stand-alone exoskeleton is designed to manage risk by supporting the strength of waist, hip joints and lower back which are vulnerable during frequent handling of heavy objects (Yu *et al.*, 2015).

Pistolesi and Lazzerini (2020) also explored the risk assessments and control on workers lifting loads. A system which comprised of a reflective safety jacket equipped with two barometric altimeters, a triaxial accelerometer and a triaxial magnetometer was used for the risk assessment of workers when lifting heavy loads while a neural classifier uses the signals from these sensors to determine how safely a task was executed (Pistolesi and Lazzerini, 2020). The neural classifier after being tested had an accuracy of 95.6% (Pistolesi and Lazzerini, 2020).

Design for safety

A study was conducted by Alabdulkarim *et al.* (2019) which compared the effects of three different designs of exoskeletons on the physical demands of workers conducting a drilling session. The study revealed that the designs of exoskeletons with supernumerary arms had more physical demands on the lower back which adversely affected task performance, the full design increased perceived demand on the lower extremity which are the body parts from the hips to the toes while designs mainly supporting the shoulder reduced the perceived demands at the upper extremity which consists of the forearm, upper arm and hand (Alabdulkarim *et al*, 2019).

Types of occupational safety and health hazards addressed by exoskeletons

The type of OSH hazard that was addressed by a postural-assist exoskeleton in the study conducted by Ogunseiju *et al.* (2021) was manual handling which involved repetitive lifting, moving and placing of wooden planks. The body kinematics of those manually handling wooden planks were measured using Yost labs 3-space sensor data logger while activities were captured with a video camera for verification purposes (Ogunseiju *et al.*, 2021). It was, however, observed that even though constant use of exoskeletons can aid workers in carrying out manual handling tasks safely, exoskeletons lead to a reduction in the range of motion during manual handling of wooden planks and an increase in completion time (Ogunseiju *et al.*, 2021). In another dimension of the application of exoskeletons in addressing hazards inherent in manual handling tasks, Pistolesi and Lazzerini (2020) presented a system that combines data collected from two barometric altimeters mounted on a safety jacket while using a neural classifier to determine how safely a worker is executing a manual handling task. The system effectively monitored workers' postures during manual handling tasks and provided visual reports for a risk manager to easily assess the level of risk of such workers (Pistolesi and Lazzerini, 2020).

Types of occupational safety and health conditions addressed by exoskeletons

The types of OSH conditions addressed by exoskeletons in literature is primarily WMSDs, which constitutes a severe problem in the construction industry (Ogunseiju *et al.*, 2021). For instance, in the UK construction industry, WMSDs account for over 50% of self-reported work-related illnesses (Health and Safety Executive, 2021). Manual handling, which is predominant in the construction industry, exposes workers to the risks of WMSDs. WMSDs can be addressed by using exoskeletons which assists workers to work in safer postures (Ogunseiju *et al.*, 2021). An aspect of WMSDs addressed by exoskeletons is back pain, which affects about one-third of construction workers worldwide and it is one of the biggest causes of absences of workers from work (Pistolesi and Lazzerini, 2020). A wearable sensor that assesses the risks of back injuries of workers while lifting loads was presented. It was concluded that the system could improve the safety level of workers and reduce lost days (Pistolesi and Lazzerini, 2020).

CHALLENGES ASSOCIATED WITH THE APPLICATION OF EXOSKELETONS TO MANAGE CONSTRUCTION OSH

The use of exoskeletons is helpful in addressing construction OSH conditions, notably WMSDs. There are, however, some challenges that come with the use of exoskeletons. One of the challenges that has been identified from literature is the increase in the completion time of activities while using exoskeletons (Ogunseiju *et al.,* 2021). Also, the wearers of exoskeletons experienced discomfort on their back when carrying out activities and this could have a negative impact on the prevalence of the use of exoskeletons in the construction industry (Ogunseiju *et al.*, 2021).

The challenges of exoskeletons highlighted by Alabdulkarim *et al.* (2019) shows that exoskeletons can come in different designs such as full-body exoskeletons, upper-body exoskeletons or lower body exoskeletons. Each different arrangement of the exoskeletons could produce unexpected consequences, such as increasing physical demands on other areas of the body while decreasing the demand on the target body regions (Alabdulkarim *et al.* 2019). Hence, each different configuration needs to be assessed and controlled to ensure those unwanted effects do not harm the wearers. Furthermore, as construction activities are commonly outdoor in different weather conditions, the efficiency of the exoskeletons may be tampered by such conditions. Aligned to this, the use of exoskeletons in conditions consisting of muddy or uneven surfaces could affect the balance of the wearer while walking (Kim *et al.*, 2019). In addition, the contact of the wearer's skin with the exoskeletons could result into hygiene issues or allergic reactions on the wearer (Kim *et al.*, 2019).

Another challenge associated with exoskeletons is that they might not be usable with other PPEs such as fall-arrest harnesses as it might be too cumbersome to wear or the exoskeleton could come into conflict with the harness (Kim *et al.*, 2019). In addition, workers might feel the use of exoskeletons will give the false impression of weakness (Kim *et al.*, 2019). On the other hand, similar to how the adoption of new technologies can stimulate unintended consequences/behaviours among users (Cameron and Webster, 2005; Sakamoto, 2019), the use of exoskeletons could potentially induce unsafe attitudes and behaviours in construction workers e.g. a worker having the impression that the device makes them 'super human' resulting in reduced attention to safety or increased engagement in unsafe behaviours.

FUTURE DIRECTIONS FOR RESEARCH AND PRACTICE

Some of the studies that have tested the application of exoskeletons have not used actual construction site workers (Alabdulkarim *et al.*, 2019; Ogunseiju *et al.*, 2021). It is recommended that further works should be done to examine the potential of a postural-assist exoskeletons for manual handling tasks on construction site workers. The study of construction workers instead of students could provide a better representation of the activities performed on construction sites as construction workers can experience less difficulty in performing the tasks thereby using lesser time in completing the activities. Moreover, addressing the completion time could be useful because a lesser completion time in executing construction tasks could play a huge role in ensuring the completion of the entire construction project within the stipulated timeframe and it could also make up for other time lapses that might have occurred in other activities of a construction project. During the examination of the use of exoskeletons by construction workers for manual handling of heavy loads, the physiological conditions of the workers, such as the muscle activities of body parts and the metabolic demands, should also be assessed because it could contain information on the amount of stress the body experiences during manual handling. The understanding of this information could be vital in identifying effective interventions to WMSDs and other related diseases during manual handling. A further study should determine the relationship between fatigue and the reduced back flexion muscle loading. It is also recommended that studies should be conducted on how to improve the designs of the exoskeletons so that wearers will feel far less discomfort and be able to complete activities at a lesser time while wearing the exoskeleton.

Further studies could be conducted on the impact of exoskeletons on the manual handling of tasks involved in different construction trades such as plumbing, glazing, and roofing. Studies can also be done to compare the effects of exoskeletons on the workers of these different trades. Demographic data such as age, height and weight of participants should be considered while performing the experiments on these different construction trades. Finally, further studies could be conducted on smart devices as a substitute for the use of Shimmer sensors on reflective safety jackets to perform real-time detection of unsafe procedures to provide workers with instant notifications after they have executed an incorrect task, with personalised instructions on how to perform the task safely.

In addition to the suggested studies, it would be useful for researchers to investigate potential unintended consequences of exoskeletons for workers' OSH. This is important given that introduction of new technologies does not always yield their intended outcomes. It would also be useful for future studies to focus on evaluating the effectiveness of different exoskeletons in terms of the OSH of construction workers during work in different weather or site terrain conditions. The limited research within developing countries context, juxtaposed against the acuteness of OSH problems in those countries ought to stimulate research around the role of exoskeletons (and more broadly emerging technologies) in construction OSH management in those regions.

CONCLUSIONS

This study conducted a systematic review of literature on the application of exoskeletons for construction OSH management. The study observed that manual handling which is a common task in the construction industry causes WMSDs among construction workers. It was also observed that exoskeletons can reduce the physical demands of manual handling and thereby making it suitable for addressing WMSDs. The use of exoskeletons, however, has some challenges which includes the increase of the completion time of performing construction activities. Due to the challenges, it is therefore necessary for further research to be conducted. Further research includes investigating how to improve the design of exoskeletons in order to reduce the completion time it takes to execute a task while wearing the exoskeleton. It is also necessary to conduct experiments to ascertain the OSH impacts of exoskeleton on construction workers and for different construction trades and different weather or site terrain conditions.

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REFERENCES

Afzal, M., Shafiq, M.T. and Al Jassmi, H. (2021) 'Improving construction safety with virtual-design construction technologies - A review', *Journal of Information Technology in Construction*, 26(April), pp. 319–340. Available at: https://doi.org/10.36680/j.itcon.2021.018.

Akinlolu, M., Haupt, T.C., Edwards, D.J. and Simpeh, F. (2020) 'A bibliometric review of the status and emerging research trends in construction safety management technologies', *International Journal of Construction Management*, 0(0), pp. 1–13. Available at: https://doi.org/10.1080/15623599.2020.1819584.

Alabdulkarim, S., Kim, S. and Nussbaum, M.A. (2019) 'Effects of exoskeleton design and precision requirements on physical demands and quality in a simulated overhead drilling task', *Applied Ergonomics*, 80(August 2018), pp. 136–145. Available at: https://doi.org/10.1016/j.apergo.2019.05.014.

Alqahtani, M., Cooper, G., Diver, C. and Bártolo, P.J. (2021) 'Exoskeletons for Lower Limb Applications: A Review', in *Bio-Materials and Prototyping Applications in Medicine*. Second Edi. Available at: https://doi.org/10.1007/978-3-030-35876-1.

Amediya, F. (2016) *Robotics and Automation in Construction*. Mangalam College of Engineering, Mangalam, India. Available at: https://doi.org/10.13140/RG.2.1.1751.6566.

Bosch, T., van Eck, J., Knitel, K. and de Looze, M. (2016) 'The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work', *Applied Ergonomics*, 54, pp. 212–217. Available at: https://doi.org/10.1016/j.apergo.2015.12.003.

Bureau of Labor Statistic (2021) *National Census Of Fatal Occupational Injuries in 2020*, *Bureau of Labor Statistic*. Available at: https://www.bls.gov/iif/oshwc/cfoi/cftb0340.htm (Accessed: 17 June 2022).

Cameron, A.F. and Webster, J. (2005) 'Unintended consequences of emerging communication technologies: Instant messaging in the workplace', *Computers in Human Behavior*, 21(1), pp. 85–103. Available at: https://doi.org/10.1016/j.chb.2003.12.001.

Chen, J., Qiu, J. and Ahn, C. (2017) 'Construction worker's awkward posture recognition through supervised motion tensor decomposition', *Automation in Construction*, 77, pp. 67–81. Available at: https://doi.org/10.1016/j.autcon.2017.01.020.

Da Costa, B.R. and Vieira, E.R. (2010) 'Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies', *American Journal of Industrial Medicine*, 53, pp. 285–323. Available at: https://doi.org/10.1002/ajim.20750.

Darko, A., Chan, A.P.C., Yang, Y. and Tetteh, M.O. (2020) 'Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs', *Computers in Industry*, 123. Available at: https://doi.org/10.1016/j.compind.2020.103327.

Edwards, D.J., Rillie, I., Chileshe, N., Lai, J., Hosseini, M.R. and Thwala, W.D. (2019) 'A field survey of hand–arm vibration exposure in the UK utilities sector', *Engineering, Construction and Architectural Management*, 27(9).

Farghaly, K., Collinge, W., Mosleh, M.H., Manu, P. and Cheung, C.M. (2021) 'Digital information

technologies for prevention through design (PtD): a literature review and directions for future research', *Construction Innovation* [Preprint]. Available at: https://doi.org/10.1108/CI-02-2021-0027.
Gopura, R.A.R.C., Kiguchi, K. and Bandara, D.S.V. (2011) 'A brief review on upper extremity robotic exoskeleton systems', *2011 6th International Conference on Industrial and Information Systems, ICIIS 2011 - Conference Proceedings*, 8502, pp. 346–351. Available at: https://doi.org/10.1109/ICIINFS.2011.6038092.
Health and Safety Executive (2020) *Manual Handling Operations Regulations: A Brief Guide*, *Health and Safety Executive*. Available at: https://www.hse.gov.uk/pubns/indg143.htm (Accessed: 17 June 2022).
Health and Safety Executive (2021) 'Construction statistics in Great Britain, 2021', *Health and Safety Executive* [Preprint], (December). Available at: https://www.hse.gov.uk/statistics/industry/construction.pdf.
Health and Safety Executive (2022) *Risk at Work - Manual Handling*, *Health and Safety Executive*. Available at: https://www.hse.gov.uk/toolbox/manual.htm (Accessed: 8 June 2022).
Hondzinski, J.M., Ikuma, L., De Queiroz, M. and Wang, C. (2019) 'Effects of exoskeleton use on movement kinematics during performance of common work tasks: A case study', *Work*, 61(4), pp. 575–588. Available at: https://doi.org/10.3233/WOR-162827.
Hou, L., Wu, S., Zhang, G.K., Tan, Y. and Wang, X. (2021) 'Literature review of digital twins applications in construction workforce safety', *Applied Sciences (Switzerland)*, 11(1), pp. 1–21. Available at: https://doi.org/10.3390/app11010339.
Howard, J., Murashov, V. V., Lowe, B.D. and Lu, M.L. (2020) 'Industrial exoskeletons: Need for intervention effectiveness research', *American Journal of Industrial Medicine*, 63(3), pp. 201–208. Available at: https://doi.org/10.1002/ajim.23080.
Huysamen, K., de Looze, M., Bosch, T., Ortiz, J., Toxiri, S. and O'Sullivan, L.W. (2018) 'Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks', *Applied Ergonomics*, 68(November 2017), pp. 125–131. Available at: https://doi.org/10.1016/j.apergo.2017.11.004.
ILO (2015) *Construction: a hazardous work*. Available at: https://www.ilo.org/safework/areasofwork/hazardous-work/WCMS_356576/lang--en/index.htm (Accessed: 16 March 2022).
Institute of Management (2021) *World Digital Competitiveness Rankings - IMD*. Available at: https://www.imd.org/centers/world-competitiveness-center/rankings/world-digital-competitiveness/ (Accessed: 31 March 2022).
Kazerooni, H. (2008) 'A review of the exoskeleton and human augmentation technology', in *ASME Dynamic Systems and Control Conference*. Michigan: American Society of Mechanical

Engineers, pp. 1539–1547. Available at: https://doi.org/10.1115/dscc2008-2407.
Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D.M. and Nussbaum, M.A. (2019) ‘Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions’, *IISE Transactions on Occupational Ergonomics and Human Factors*, 7(3–4), pp. 185–191. Available at: https://doi.org/10.1080/24725838.2018.1561557.
Kim, S., Nussbaum, M.A. and Smets, M. (2022) ‘Usability, User Acceptance, and Health Outcomes of Arm-Support Exoskeleton Use in Automotive Assembly: An 18-month Field Study’, *Journal of Occupational and Environmental Medicine*, 64(3), pp. 202–211. Available at: https://doi.org/10.1097/JOM.0000000000002438.
Kumar, V.S.S., Prasanthi, I. and Leena, A. (2021) ‘Robotics and automation in construction industry’, *International Research Journal of Engineering and Technology*, 8(2), pp. 104–109. Available at: https://doi.org/10.1061/41002(328)3.
de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S. and O’Sullivan, L.W. (2016) ‘Exoskeletons for industrial application and their potential effects on physical work load’, *Ergonomics*, 59(5), pp. 671–681. Available at: https://doi.org/10.1080/00140139.2015.1081988.
Manu, P., Emuze, F., Saurin, T.A. and Hadikusumo, B.H.W. (2019) ‘An introduction to construction health and safety in developing countries’, in *Construction Health and Safety in Developing Countries*. 1st edn. Routledge, pp. 1–11. Available at: https://doi.org/10.1201/9780429455377/CONSTRUCTION-HEALTH-SAFETY-DEVELOPING-COUNTRIES-PATRICK-MANU-FIDELIS-EMUZE-TARCISIO-ABREU-SAURIN-BONAVENTURA-HADIKUSUMO.
Martínez-Aires, M.D., López-Alonso, M. and Martínez-Rojas, M. (2018) ‘Building information modeling and safety management: A systematic review’, *Safety Science*, 101(August 2017), pp. 11–18. Available at: https://doi.org/10.1016/j.ssci.2017.08.015.
Meo, S.A., Alsaaran, Z.F., Alshehri, M.K., Khashougji, M.A., Almeterk, A.A.Z., Almutairi, S.F. and Alsaeed, S.F. (2013) ‘Work-related musculoskeletal symptoms among building construction workers in Riyadh, Saudi Arabia’, *Pakistan Journal of Medical Sciences*, 29(6). Available at: https://doi.org/10.12669/pjms.296.4052.
Nassereddine, H., Veeramani, D. and Hanna, A.S. (2022) ‘Design, Development, and Validation of an Augmented Reality-Enabled Production Strategy Process’, *Frontiers in Built Environment*, 8(February), pp. 1–22. Available at: https://doi.org/10.3389/fbuil.2022.730098.
Nigam, V. and Talcott, C. (2022) ‘Automated construction of security integrity wrappers for Industry 4.0 applications’, *Journal of Logical and Algebraic Methods in Programming*, 126, p. 100745. Available at: https://doi.org/10.1016/j.jlamp.2021.100745.
O’Sullivan, L., Nugent, R. and van der Vorm, J. (2015) ‘Standards for the Safety of Exoskeletons

Used by Industrial Workers Performing Manual Handling Activities: A Contribution from the Robo-Mate Project to their Future Development', *Procedia Manufacturing*, 3(Ahfe), pp. 1418–1425. Available at: https://doi.org/10.1016/j.promfg.2015.07.306.

Ogunseiju, O., Olayiwola, J., Akanmu, A. and Olatunji, O.A. (2021) 'Evaluation of postural-assist exoskeleton for manual material handling', *Engineering, Construction and Architectural Management* [Preprint]. Available at: https://doi.org/10.1108/ECAM-07-2020-0491.

Oke, A., Aigbavboa, C. and Mabena, S. (2017) 'Effects of Automation on Construction Industry Performance', in *Second International Conference on Mechanics, Materials and Structural Engineering (ICMMSE 2017)*, pp. 370–374. Available at: https://doi.org/10.2991/icmmse-17.2017.61.

de Oliveira Sato, T. and Cote Gil Coury, H.J. (2009) 'Evaluation of musculoskeletal health outcomes in the context of job rotation and multifunctional jobs', *Applied Ergonomics*, 40(4), pp. 707–712. Available at: https://doi.org/10.1016/j.apergo.2008.06.005.

Perrier, N., Bled, A., Bourgault, M., Cousin, N., Danjou, C., Pellerin, R. and Roland, T. (2020) 'Construction 4.0: A survey of research trends', *Journal of Information Technology in Construction*, 25, pp. 416–437. Available at: https://doi.org/10.36680/J.ITCON.2020.024.

Petrillo, A., Felice, F. De, Cioffi, R. and Zomparelli, F. (2018) 'Fourth Industrial Revolution: Current Practices, Challenges, and Opportunities', *Digital Transformation in Smart Manufacturing*, pp. 1–20. Available at: https://doi.org/10.5772/intechopen.72304.

Pistolesi, F. and Lazzerini, B. (2020) 'Assessing the Risk of Low Back Pain and Injury via Inertial and Barometric Sensors', *IEEE Transactions on Industrial Informatics*, 16(11), pp. 7199–7208. Available at: https://doi.org/10.1109/TII.2020.2992984.

Reinhardt, D. *et al.* (2020) 'CoBuilt 4.0: Investigating the potential of collaborative robotics for subject matter experts', *International Journal of Architectural Computing*, 18(4), pp. 353–370. Available at: https://doi.org/10.1177/1478077120948742.

Ren, B., Li, H., Chen, J. and Wang, Y. (2021) 'Gait trajectory-based interactive controller for lower limb exoskeletons for construction workers', *Computer-Aided Civil and Infrastructure Engineering*, pp. 1–15. Available at: https://doi.org/10.1111/mice.12756.

Robotics (2022) *What is Robotics? What are Robots? Types & Uses of Robots.*, *Built In*. Available at: https://builtin.com/robotics (Accessed: 9 June 2022).

RoboticsBiz (2021) *Active vs. passive exoskeletons explained*. Available at: https://roboticsbiz.com/active-vs-passive-exoskeletons-explained/ (Accessed: 29 June 2022).

Ruggiero, A. and Salvo, S. (2016) *Robotics in Construction*. Worcester Ploytechnic Institute. Available at: https://web.wpi.edu/Pubs/E-project/Available/E-project-032316-150233/unrestricted/FinalReport.pdf.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015)

'Future of Productivity and Growth in Manufacturing', *Boston Consulting Group*, 11. Available at: https://doi.org/10.1007/s12599-014-0334-4.

Sakamoto, A. (2019) 'Unintended consequences of translation technologies: from project managers' perspectives', *Perspectives: Studies in Translation Theory and Practice*, 27(1), pp. 58–73. Available at: https://doi.org/10.1080/0907676X.2018.1473452.

Sirinterlikci, A., Karaman, A. and Imamoglu, O. (2012) 'Automation and robotics in processes', in *Instrument Engineers' Handbook: Fourth Edition*, pp. 158–168. Available at: https://doi.org/10.1201/b11093-11.

Srinivas, K. (2019) 'Process of Risk Management', in *Perspectives on Risk, Assessment and Management Paradigms*, pp. 0–16. Available at: https://doi.org/10.5772/intechopen.80804.

Viteckova, S., Kutilek, P. and Jirina, M. (2013) 'Wearable lower limb robotics: A review', *Biocybernetics and Biomedical Engineering*, 33(2), pp. 96–105. Available at: https://doi.org/10.1016/j.bbe.2013.03.005.

Wang, X., Dong, X.S., Choi, S.D. and Dement, J. (2017) 'Work-related musculoskeletal disorders among construction workers in the United States from 1992 to 2014', *Occupational and Environmental Medicine*, 74(5), pp. 374–380. Available at: https://doi.org/10.1136/oemed-2016-103943.

Yu, H., Choi, I.S., Han, K.L., Choi, J.Y., Chung, G. and Suh, J. (2015) 'Development of a stand-Alone powered exoskeleton robot suit in steel manufacturing', *ISIJ International*, 55(12), pp. 2609–2617. Available at: https://doi.org/10.2355/isijinternational.ISIJINT-2015-272.

Zurada, J. (2012) 'Classifying the risk of work related low back disorders due to manual material handling tasks', *Expert Systems with Applications*, 39(12), pp. 11125–11134. Available at: https://doi.org/10.1016/j.eswa.2012.03.043.