ICCEPM 2024 https://dx.doi.org/10.6106/ICCEPM.2024.1027
The 10th International Conference on Construction Engineering and Project Management
Jul. 29-Aug.1, 2024, Sapporo

Applications, Challenges, and Future Research Directions for Passive Exoskeletons in the Construction Industry: A Critical Review

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Abstract: Much labour is required in the labour-intensive construction sector for workers to do physically taxing jobs like plastering, paving, surfacing, material lifting, hauling, scaffolding, etc. Passive exoskeletons have been advocated and examined in previous studies to reduce physical demands, improve work efficiency, and prevent work-related musculoskeletal disorders in construction workers. This review study examined previous studies performed on passive exoskeletons in construction or other occupational domains with the aim of finding the working principles and design requirements of the passive exoskeletons, their applicability and usability in occupational settings, and the potential challenges in their adoption, thereby finding future research directions that can overcome those challenges. Three working principles were identified: muscle assistance, joint load reduction, and maintaining proper posture. The design requirements to achieve one or more of these working principles may have a few undesired effects on the usability of the passive exoskeletons, like discomfort, unnecessary weight of the passive exoskeleton, difficulty in operation, restricted range of motion of the joints supported, and the unaffordability of these exoskeletons by the workers. Passive exoskeletons were reported to have a range of positive effects, like reducing muscle effort and improving the endurance of the workers. The study concluded that there needs to be sufficient research on real construction workers in a real construction environment to convince the workers and managers to accept passive exoskeletons. To improve the usability of passive exoskeletons, fundamental changes in design are needed through further research so that the exoskeleton can support workers in multitasking rather than a single function. They also need to become more affordable, and the other undesired negative effects of passive exoskeletons should also be addressed.

Key words: Passive exoskeletons, construction workers, design, muscle, work-related musculoskeletal disorders.

1. INTRODUCTION

In the construction industry, workers are extensively engaged in physically demanding tasks such as lifting and hauling materials due to their labour-intensive nature [1]. The physically demanding tasks in the construction industry, such as lifting and hauling materials, often involve sustained and repetitive work performed in challenging postures like kneeling, crouching, and stooping. These tasks put workers at a high risk of experiencing work-related musculoskeletal disorders (WMSDs), which can lead to occupational injuries and illnesses [2].

The use of exoskeleton technologies is gaining attention in the construction industry to reduce WMSDs and improve worker productivity [3]. External supports by wearing exoskeleton suits aim to alleviate muscle overload and fatigue from repetitive tasks and enhance muscle strength and endurance [1]. Exoskeletons can be categorized into two types based on their energy sources: active and passive. Active exoskeletons offer greater augmentation capabilities but tend to be heavier and more costly for construction workers. Passive exoskeletons, on the other hand, store energy in unpowered devices and release it when needed without requiring sophisticated batteries or recharging. This makes passive exoskeletons a more attractive intervention for improving productivity and reducing WMSDs in construction [4, 5].

Experimental studies have shown that passive exoskeletons can significantly reduce muscular activity (30%-57%) during bending tasks [6, 7]. In the construction industry, recent studies have reported favourable results for the use of passive exoskeletons in tasks such as manual material handling and rebar work [3, 4]. Despite these benefits, barriers to adoption remain due to concerns about health, safety, usability, and return on investment [8]. Workers also face the possibility of unforeseen or incompatible interaction loads, which can restrict their movement and lead to discomfort [9]. Predicting these effects is challenging because passive exoskeleton designs, mechanisms, and materials vary across products. Additionally, the dynamic nature of construction work raises questions about the effectiveness of available passive exoskeletons for different tasks and environments. Therefore, a comprehensive understanding of passive exoskeleton systems, their working principles, and potential challenges is necessary for informed decision-making and maximizing the benefits of exoskeletons in construction.

Even though several systematic reviews have been conducted by McFarland and Fischer [10], De Looze et al. [5], Toxiri et al. [11], Bogue R. [12], Ashta et al. [13], Zhu et al. [2], and Kermavnar et al. [14], among others, the working mechanisms have not been fully investigated yet. There is a wide range of variations in terms of mechanical systems and design approaches according to varying working mechanisms. Thus it is not easy to understand the impact of these variations on both benefits and side-effects of passive exoskeletons. Therefore, this study aims to investigate fundamental working principles of existing passive exoskeletons, associated usability issues and remaining challenges of passive exoskeleton applications in the construction industry. The findings of this study will assist researchers and developers in addressing existing challenges by customizing exoskeletons with improved mechanical designs for dynamic construction tasks. Additionally, construction managers will be able to make informed decisions regarding the suitability of specific exoskeleton products based on their unique work contexts.

2. METHODOLOGY

The goal of the study was to investigate passive exoskeleton design principles for the construction sector. Using the search terms "passive" AND "exoskeleton" AND "construction," searches were done in Scopus, Embase, PubMed, and Web of Science. In each database, there were 41, 9, 11, and 42 studies altogether. Of the forty-one studies listed in Scopus, twenty-five were inaccessible or unrelated, and sixteen were pertinent. Nine studies were found in Embase; two of them were duplicates or unrelated. Since Scopus or Embase previously covered the relevant studies, no new ones could be discovered in PubMed. Out of 42 relevant studies, five new ones were found using the Web of Science; the remaining 37 were either duplicates or unrelated. Nine more studies could also be found on Google Scholar.

3. WORKING PRINCIPLES, APPLICATIONS AND EFFECTS OF PASSIVE EXOSKELETONS

Through a comprehensive literature search, it has been determined that the working principles of passive exoskeletons can be broadly classified into three categories: (a) muscle assistance [15, 16], (b) joint load reduction [17], and (c) maintaining the proper posture [18]. It is worth noting that each passive exoskeleton operates on one or more of these three principles, as illustrated in Figure 1, with the aim of assisting workers in various applications.

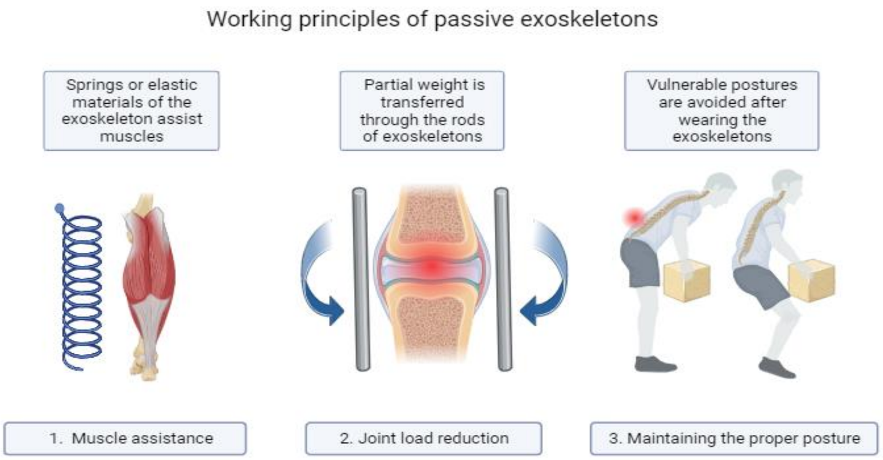

Figure 1. Passive exoskeletons operate based on three fundamental working principles.

In this section, the applications of passive exoskeletons are assessed by analyzing their impact on various parameters in industrial activities. These parameters can be divided into physiological (muscle activation, heart rate, oxygen consumption, metabolic rate), biomechanical (kinematics, postural control, compression forces, ground reaction forces), and subjective (productivity, quality, discomfort, pain, prevention of musculoskeletal disorders, task completion time, endurance).

Prior research has indicated that passive back support exoskeletons have the potential to decrease the activity of trunk extensor muscles [6, 7, 19-22]. Some studies have reported a decrease in heart rate with passive exoskeletons [23-26], while others have found an increase [27]. According to Whitfield et al., the use of an on-body personal lift assistive device (PLAD) did not have an impact on oxygen consumption during a continuous lifting task. They concluded that the PLAD decreased muscle activity but not enough to change oxygen uptake [28]. Qu et al.'s study found no significant difference in oxygen consumption when a passive back support exoskeleton was used during lifting tasks [29]. Maurice et al., in their study on passive shoulder exoskeleton, reported 33% lower oxygen consumption in overhead tasks [30].

Bennett et al. found that wearing passive exoskeletons reduced the natural shoulder ROM in construction workers [9]. Simon et al. reported that using a passive back support exoskeleton led to a 1.5^{o} increase in ankle dorsiflexion, as well as decreases of 2.6^{o} and 2.3^{o} in knee flexion and Shoulder-Hip-Knee angles [31]. Baltrusch et al. observed no significant changes in kinematics with a back support exoskeleton [32]. Luger et al. discovered that wearing a passive lower-limb exoskeleton affected the wearers' centre of pressure, with a more posterior location during exoskeleton use and sitting high [33]. Koopman et al. found that the exoskeleton reduced compression force by 13-21% at L5-S1 during static bending and decreased peak compression force by an average of 14% during lifting [34].

Several studies have investigated the effects of exoskeletons on various subjective parameters related to task completion time, performance, quality of work, discomfort, and injury prevention. Ogunseiju et al. found that wearing a back exoskeleton increased task completion time during lifting [35]. On the other hand, de Vries et al. reported no change in performance or quality of work among plasterers after using an exoskeleton for six weeks [36]. Gonsalves et al. found that concrete workers using a back support exoskeleton experienced discomfort in the chest, and prolonged use increased discomfort in the chest, back, thighs, upper arm, and shoulder [37]. A survey by Okpala et al. showed that exoskeletons could prevent 30 to 40% of work-related musculoskeletal disorder (WMSD) injuries [38]. Bosch et al. reported that exoskeleton use increased the endurance period for static holding in the forward-bent trunk position by three times compared to no exoskeleton use [6]. Similarly, Spada et al. reported increased endurance time with an upper limb exoskeleton [39]. Kim et al. reported minimal effects of the exoskeleton on slip- and trip-related fall risks during level walking [40]. Park et al. reported improved trunk stability and reduced slip risk due to back support exoskeleton use [41].

4. CHALLENGES IN THE USE OF PASSIVE EXOSKELETONS IN THE CONSTRUCTION INDUSTRY

Passive exoskeletons are developed with specific working principles to support workers in various applications. However, these designs can potentially result in undesired effects that pose challenges to their usability within the construction industry. These challenges can be classified into three categories: those intrinsic to the exoskeleton design, those intrinsic to the user, and those arising from external factors.

Challenges inherent to the design of exoskeletons encompass discomfort, limitations on ROM that impede job duties, loss of functionality, ill-fitting configurations, altered joint kinematics, excessive force application, difficulties with donning and doffing, an increase in non-targeted muscle activation and cardiac workload, heightened task errors, and heavyweight.

A previous study has reported that a back support exoskeleton was perceived as mildly annoying [42]. Additional research has indicated that users expressed dissatisfaction with exoskeletons due to limitations on movement and discomfort caused by tight straps on the legs or arms [9]. Näf et al. conducted a study showing that utilizing flexible beams as a back interface significantly increased trunk range of motion (ROM) by over 25% (24.5°) compared to a rigid alternative in the sagittal plane [43].

Due to long-term wearing of the back support exoskeletons, the loss of forward bending function may occur, which means that with longer usage, the wearer may develop reduced trunk flexion ROM. The exoskeletons are also reported to interfere strongly with the safety harnesses and tool straps of concrete workers, which can be considered a major challenge to the adoption of exoskeletons in the construction industry [37]. An overextended knee position was noted during the holding task for a passive back exoskeleton Laevo, which may pose health problems if the exoskeleton is used for extended periods [44]. According to Erezuma et al., the exoskeleton constrained the movement of the centre of mass in the caudal direction while promoting greater motion in the anterior direction [45].

Park et al. have reported that high external torques generated by the passive back support exoskeleton caused increased gait variability and changes in step width during walking [41]. Junius et al. reported a long donning time for the hip exoskeleton [46]. Qu et al. examined the effects of an industrial passive, assistive exoskeleton for the back while handling work and reported that after wearing this exoskeleton, the activity of the shoulder and thigh muscles was increased. They also found that the inertia and the mass of the exoskeleton greatly increased the cardiac frequency [29]. Abdulkarim et al. examined the effects of an exoskeleton with a supernumerary arm in a simulated overhead drilling task and reported increased errors with increased task precision demands [17]. Another design factor to consider in passive exoskeleton devices is bulkiness. Several exoskeletons weigh more than 4 kg, which will be quite cumbersome for the wearer to wear all the time. For example, EksoVest™'s weight is 4.3 kg, ShoulderX weighs around 5.3 kg and Robo-Mate around 7.2 kg. (start from here 7/2/2024)

Intrinsic challenges related to the user involve the need for familiarization, a certain level of physical fitness required for proper exoskeleton use, potential muscle deconditioning, and the risk of injuries. According to Park et al., wearers needed time to familiarize themselves with the exoskeletons and adapt to them [41]. According to Goršič et al., informal discussions with the participants revealed that individuals with lower levels of physical fitness generally faced greater challenges when using the back support exoskeleton [42]. In a systematic review conducted by Ali et al., it was reported that passive exoskeletons featuring rigid structures could potentially lead to muscle deconditioning when used for prolonged periods [44]. Furthermore, if wearers are not adequately trained, there is a possibility that the exoskeleton itself could increase the risk of injury [47].

Challenges due to other external factors include the need for more research data and overpricing. More data is needed to support the benefits and effectiveness of exoskeletons in relation to financial and other risks because their application in construction workplaces is very limited [48]. Currently, exoskeletons can cost anywhere from USD 5,000 to USD 100,000, making them unaffordable for workers to buy for themselves. In addition, there is a fee for continuous exoskeleton maintenance that is necessary to guarantee workers' safety [48].

5. FUTURE RESEARCH DIRECTIONS AND DESIGN REQUIREMENTS

This section deals with future research directions and design requirements that should be explored to address the challenges associated with the adoption of passive exoskeletons in the construction industry.

The contact part of the exoskeleton should incorporate soft pads to minimize pressure and prevent skin injuries. To enhance comfort, it is crucial to distribute pressure evenly over a large body area and ensure proper ventilation through pores in the padded regions. Additionally, maintaining appropriate temperature and ventilation in enclosed spaces is important. Before utilizing the exoskeleton, a thorough inspection should be conducted to identify any visible defects. Furthermore, it is essential to ensure that non-targeted joints are not restricted in their ROM. Exoskeletons should be designed for easy donning and doffing, facilitating efficient and seamless use. Adjustable sizes for different body parts should be available to ensure a proper fit for each wearer. Sufficient space should be provided to accommodate backrests, safety harnesses, and tool belts. Finally, kinematic aspects should be tested on subjects, and effective solutions that do not hinder natural body movement should be implemented.

The exoskeletons should allow wearers to adjust the force intensity to meet their specific needs. Additionally, minimizing the weight of the exoskeleton and any accompanying structures is important to enhance comfort and usability. Proper training and familiarization programs should be implemented to ensure wearers are adequately prepared before using the exoskeletons in real work environments. These training sessions should be systematic, providing sufficient time and diverse tasks to facilitate safe and effective use of the exoskeleton devices. Simplifying the design of the exoskeletons is advised, and wearers should receive appropriate training on how to operate them. Work tasks should be designed to be less complex, taking into consideration the use of exoskeletons. It is essential to obtain and review the instruction manual provided by the exoskeleton manufacturer to ensure proper usage. Only exoskeletons that have been proven effective should be utilized. To maintain safety and functionality, it is crucial to limit the duration of exoskeleton use or complement it with strengthening activities. Regular checks by skilled technologists or technicians should be conducted to ensure the ongoing performance of the exoskeletons. Finally, adherence to the manufacturer's guidelines regarding the scope of use, such as weightlifting limits, is of utmost importance. It is imperative to conduct further research studies involving actual construction workers performing real construction tasks. This will provide valuable insights and data necessary to evaluate the effectiveness and practicality of exoskeletons in the construction industry. Additionally, exploring the potential for mass production can help reduce the cost of exoskeletons, enabling broader accessibility. To cater to the multitasking nature of construction tasks, exoskeletons should be designed to support multiple body parts simultaneously.

6. CONCLUSIONS

This review investigated working principles, usability challenges, and future research directions to address exoskeleton challenges in construction. It outlined three common working principles in passive exoskeletons: muscle assistance, joint load reduction, and maintaining proper posture. However, negative effects were also identified. High prices and limited multitasking suitability hinder passive exoskeleton popularity in construction. Most designs target specific tasks like bending or lifting rather than accommodating dynamic multitasking. The study proposes research directions and mechanical design changes to enhance usability and enable multitasking. Limitations include the need for more data from real construction settings and a lack of discussion on biomechanics and active exosuits in construction. Comparing active exosuits to passive ones presents potential for future research.

ACKNOWLEGEMENTS

This research study was supported by the BRE Research Incentive Scheme (P0046575) from Hong Kong Polytechnic University.

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