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Critical review on applications and roles of exoskeletons in patient handling

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Abstract

Musculoskeletal Disorders (MSDs) remain a major concern for workers in the healthcare industry. Healthcare workers are at high risk of work-related MSDs mainly caused by overexertion from manually handling patients. Exoskeletons may be a useful tool to help reduce the risk of MSDs during patient handling. As a review study, we surveyed articles focusing on applying exoskeletons to patient handling tasks specifically. We also reviewed relevant government databases and other studies related to Safe Patient Handling and Mobility (SPHM) programs and exoskeleton applications in general. The exoskeletons specifically designed for patient handling were found to be sparse. To have a better understanding of the needs and challenges of developing and using exoskeletons for reducing risks of work-related MSDs in healthcare workers during patient handling, this critical review (1) provided an overview of the existing issues and projected future burdens related to work-related MSDs during patient handling tasks, (2) recognized current and potential roles and applications of existing exoskeletons, and (3) identified challenges and needs for future exoskeleton products. In conclusion, we do not expect exoskeletons to replace the existing SPHM programs, but rather play a complementary role to these multi-pronged programs. We expect that emerging exoskeleton products can be introduced to uncontrolled or specialized healthcare environments. There are various expectations and requirements for an exoskeleton used in different healthcare settings. Additionally, introducing certain types of exoskeletons for patients to assist them during treatment and rehabilitation may help reduce the MSD risks to the healthcare workers.

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Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Keywords

Patient handling; Mobility; Exoskeleton; Musculoskeletal disorders

1. Introduction

Musculoskeletal disorders (MSDs) experienced by workers in the healthcare industry have been and remain a major concern. According to the U.S. Bureau of Labor Statistics (BLS), overexertion is one of the most common events leading to MSDs—over 65% of MSD cases were associated with overexertion (BLS 2017b). In 2017, the rate of overexertion injuries for hospital workers (57 per 10,000) was about twice the average across all the industries (30 per 10,000) (BLS 2017a). Costs associated with overexertion injuries in the healthcare industry were estimated to be $1.7 billion in 2015 (Bell et al., 2017). The overexertion events occurred to the healthcare workers are mainly related to repeated manual patient handling activities, often involving heavy manual lifting associated with transferring, and repositioning patients and working in extremely awkward postures. It is also worth noting that the safety of both workers and patients are at stake whenever a patient is lifted, repositioned, or transferred. The consequences of such incidents are often exceptionally costly and sometimes irreversibly tragic.

As current recommendations, Safe Patient Handling and Mobility (SPHM) programs involving the use of mechanical equipment and safety procedures have demonstrated significant reductions in the MSD rate of healthcare workers (NIOSH 2013). Successful SPHM programs are designed to include comprehensive interventions at different aspects, such as engineering, administrative and personnel controls (VA 2001). This includes large-scale purchasing and care of mechanical lift equipment, adoption of policies regarding the use of these devices, and support for employees using the devices via the establishment of training programs. Numerous studies have demonstrated that SPHM programs can significantly decrease worker injuries and lost work time (Teeple et al., 2017; Collins et al., 2004). The investments in SPHM programs can be expected to be recovered in less than five years (OSHA 2013). Despite successes with these programs, laws requiring SPHM programs in healthcare exist in only 11 of 50 states and no federal legislation has been passed to mandate SPHM programs (Weinmeyer 2016). Additionally, certain specialized healthcare environments—such as home care, mobility and rehabilitation settings, operating rooms, and imaging/radiology facilities—present unique challenges to adopting the SPHM programs. In such working environments with limited or no assistive equipment, it is often impossible to avoid manual patient handling, especially when a worker is working alone. While SPHM programs are expected to make continuous progress, the high incidence rates of MSDs among healthcare workers indicate that we still face severe challenges. Thus, there is a great need for improving the existing intervention methods and exploring non-traditional assistive technologies to reduce MSD risks in healthcare workers.

There is an ongoing movement towards human-robot collaboration in modern industry, such as implementing wearable robots (exoskeletons or exosuits) to provide the benefits of robotics while retaining the flexibility of humans. Various exoskeletons have been developed

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with the aim in augmenting and enhancing workers' strength, endurance and performance. Industries involving material and load handling have shown promising potential of exoskeleton applications (de Looze et al., 2016), which has led to the exploration of the feasibility of using exoskeletons in safe patient handling. In addition to discussing current applications of existing exoskeletons in patient handling, this review also aims to provide a better picture of the needs and challenges of developing and using exoskeletons during patient handling. Thus, in this critical review, we (1) provide an overview of the existing issues and projected burdens related to work-related MSDs during patient handling tasks; (2) recognize current and potential roles and applications of existing exoskeletons; and (3) identify challenges and needs for future exoskeleton products. Based on the review, insights are provided on the desired role and the design ideas of exoskeletons in reducing risks of work-related MSDs for healthcare workers. We hope to provide information to healthcare professionals that may help them to consider this emerging technology, and to bring interests of exoskeleton developers to this line of products which are in high demand and could be developed and deployed in a multi-pronged strategy.

2. Review criteria

The present review mainly focuses on studies investigating applications of exoskeletons in patient handling. We followed the Preferred Reporting Items for Systematic Reviews statements to identify and screen the articles (Moher et al., 2009). The search strategy and the selection criteria were presented in Fig. 1. A total of seven articles matched the inclusion criteria, which included one brief review paper (O'Connor 2021) and six original research papers (Hwang et al., 2021; Settembre et al., 2020; Turja et al., 2020; Miura et al., 2021; Cha et al., 2020; Liu et al., 2018). The original research papers were discussed in detail in section 4 (current uses of existing exoskeletons; Table 1).

In addition, a narrative review was conducted on the relevant government databases (such as BLS data) and other studies related to SPHM programs and exoskeleton applications in general to support our interpretations and predictions.

3. Current concerns and projected burdens

The current concerns and projected burdens related to work-related MSDs were discussed and predicted based on relevant government databases and literature review. Currently, there are close to 3 million registered nurses and 1.5 million nursing assistants in the united states, which are top two most populated healthcare occupations (BLS, 2018e, 2018d). In 2017, incidence rates of MSDs were 166.3 and 43.6 for nursing assistants and registered nurses, respectively, per 10,000 full-time equivalent workers (FTEs) (BLS 2017d, 2017e). As the second largest healthcare occupation, nursing assistants routinely perform patient-handling tasks (BLS 2018d). This single occupation reported 18, 090 MSD cases in 2017, which accounted for 5.2% of the total MSD cases (BLS 2017c; 2018a). As to the affected parts of the body, more than half of their MSD cases involved back injuries (BLS 2018b). The high overexertion injury rate may be partially due to the gender of the worker population, with females comprising approximately 90% of registered nurses and nursing aides (BLS, 2017f), who generally have less physical strength than male workers.

With synergistic efforts from multiple federal agencies and professional practice organizations, SPHM programs have been developed to address various needs for safe patient handling. However, despite the broad SPHM program successes, several program limitations exist, such as the inability of the lift equipment to meet practitioners' needs, the overall lack of equipment availability, and issues with equipment storage and accessibility. The availability of mechanical lift equipment was identified as one of the most common barriers to using assistive devices in patient handling, as well as staffing levels, workload, and emergent patient needs (Noble and Sweeney 2018). Along with a general lack of equipment, availability of equipment due to the accessibility of the equipment (e.g., stored too far from patients and difficult to retrieve) was noted as a frequent obstacle.

The work-related MSD burdens are projected to become unprecedentedly worse in the future due to the rapidly aging population, the obesity epidemic, and the shortage and aging of the healthcare workforce in the United States. The population aged 65 and older is expected to more than double between 2012 and 2060, representing about one in five residents as compared with one in seven today (US Census Bureau 2012). Additionally, about 42% of the U.S. population is projected to be obese by 2030 (Finkelstein et al., 2012). Combining the aging population and a rise in disease-specific risk factors (e.g., obesity), there will be significantly increased demand on the healthcare service and workers. The nursing shortage is estimated to be up to one million by 2025, and nearly half of all current nurses are approaching the traditional retirement age (Buerhaus 2008; Willis Towers Watson 2016;Aiken et al. 2009). In the near future, fewer, older and heavier healthcare workers are expected to take care of more, older and heavier patients. More specifically, how to safely handle bariatric patients poses a severe challenge to existing SPHM programs (Galinsky et al., 2021; Choi and Brings 2015).

Emerging trends in the healthcare system, such as rise in home care and safe early mobility, may result in increased work-related MSD burdens for more healthcare occupations (e.g., homecare workers and rehabilitation professionals). Patients are released from the hospital following surgery and other treatments much earlier than in the past. The average length of hospital stay was 7.5 days in 1980, compared with only 4.8 days in 2005 (NCHS 2007). More seniors plan to age in place—about 80% of adults age 50 and older intend to remain in their current homes and communities as they age (Binette and Vasold 2018). As the fastest growing occupations, combined home health aides and personal care aides are projected to add 1.2 million jobs over the 2016–2026 period (BLS 2018c). They are most likely to work in an uncontrolled environment—where workers have minimal or no control of working environment settings (such as a patient's home)—often with no or limited assistive equipment (Galinsky and Burnett 2010). There is a delicate balance between protecting client autonomy and creating safer working and care conditions (Quinn et al., 2021). Moreover, there is a cultural change of promoting early mobility while patients are in the hospital. Early mobility has shown numerous benefits to patients, such as increases in their muscle strength, functional performance, and independence after hospital discharge (Brown et al., 2009;Bakhru et al., 2015). However, supporting early mobility may impose increasing MSD risks and burden on rehabilitation professionals (such as physical therapists, occupational therapists, and their assistants/aides) who help patients with their ambulation and mobility. More than half of physical therapists (55–91%) are estimated to experience work related MSDs during their working career and one in six make career changes as a result of injury (Cromie et al. 2000; Darragh et al., 2013). Alarmingly, the MSD rates for occupational therapists increased markedly from 27 cases to 101 cases per 10,000 FTEs from 2018 to 2019 (BLS 2019). In a recent in-depth investigation of rehabilitation professional's needs in SPHM programs, it was found that many pieces of existing lift equipment does not support the rehabilitation professionals to perform therapeutic mobility, which is seen as a central role in their day to day practice (Evans et al., 2021). In a nationwide survey of physical therapist members of the acute care section of the American Physical Therapy Association, it was found that the most frequently reported program limitation is lack of available equipment (Olkowski and Stolfi 2014). Preserving the health of our healthcare staff and reducing their risks of MSDs under different working environments is already critical and will become more so during the years to come.

4. Current and potential uses of existing exoskeletons

Exoskeleton is defined as a wearable device that augments, enables, assists, and/or enhances physical activity, either static or dynamic, through mechanical interaction with the body (ASTM 2020b). Many existing exoskeletons on the market have been used to assist workers during their working tasks, such as overhead tasks and material handling (Schmalz et al., 2019; de Looze et al., 2016). Several studies have shown that muscle activity in the lower back is significantly reduced during a dynamic lifting or material handling task when wearing either a powered or passive exoskeleton (Bosch et al., 2016; Huysamen et al., 2018). The present work reviewed the studies that investigated the current applications of existing commercialized exoskeletons in patient handling tasks (review criterion shown in Fig. 1; Table 2). Additionally, we discussed the potential uses of the existing exoskeleton products in other healthcare settings (Table 2).

Current Uses.

Commercialized back- and upper-body-assist exoskeletons have been assessed for different patient handling tasks (Table 1). Three passive back-assist exoskeletons were evaluated during the simulated wheelchair-to-bed patient transfers and it was found that lower back muscle activities were significantly reduced in all three exoskeleton conditions compared to the no exoskeleton condition (Hwang et al., 2021). During the Covid-19 pandemic, a pilot study found that wearing a passive back-assist exoskeleton was helpful (based on a user survey) during a complex and strenuous prone-positioning procedure, which is frequently required by patients with severe Covid-19-related acute respiratory distress syndrome (Settembre et al., 2020). The same passive back-assist exoskeleton was also assessed in a geriatric care setting, where nurses wore the exoskeleton to assist senior patients during wheelchair transfers, eating, and toileting. Most nurses reported positive user experience and perceived usefulness, although some psychosocial concerns were raised (e.g., whether exoskeletons influence interaction and trust between workers and patients) (Turja et al., 2020). A powered back-assist exoskeleton was evaluated during a task to lift a 60-kg mannequin from a seated position to a standing position. Although the muscle activity in one of the leg muscles was found increased while wearing the exoskeleton, the subjective lumbar fatigue score was significantly decreased compared to the no-exoskeleton condition

(Miura et al., 2021). A passive shoulder-assist exoskeleton was evaluated in the operation room during a static laparoscopy operation procedure. Overall, the surgeons and the surgical team members had good acceptance and reported less fatigue experienced while wearing the exoskeleton (Cha et al., 2020; Liu et al., 2018).

Potential Uses.

While there are several studies that have investigated the use of exoskeletons in hospital settings, few studies have investigated the application of exoskeletons in home care or rehabilitation settings. The existing exoskeletons on the market, specifically back- and upper-body-assist exoskeletons, appear to have potential applications for home care workers and rehabilitation professionals (Table 2). As discussed in the previous section, home care workers and rehabilitation professionals are often not able to access assistive equipment, or their working environments would not allow to implement the SPHM programs. Daily tasks of home care workers are similar to those in hospital settings and may include dressing and bathing the patient, patient transfers (e.g., bed to wheelchair, wheelchair to toilet, wheelchair to bed), and repositioning the patient, either in bed or in a chair. Home care workers typically work alone, may only have access to one side of bed, or the bed height is not adjustable. Their daily jobs inevitably involve repetitive tasks that consist of a lot of bending and lifting, which could be helped by using back-assist exoskeletons. Similarly, for rehabilitation professionals, their daily tasks may involve helping patients do specific exercises repetitively as part of the plan of care and may require moving and lifting patients or heavy equipment (BLS 2021b; 2021a). The existing exoskeletons (e.g., back- or shoulder-assist exoskeletons) may have potential uses in some of these tasks.

5. Challenges and needs for future exoskeletons

Despite the promising pioneer work, the development of exoskeletons for safe patient handling is still in its early stage. The exoskeleton products specifically designed for patient handling or for healthcare workers are sparse. Invention and innovation are needed to develop exoskeletons to help reduce MSD risks for healthcare workers and improve care quality for patients. To help exoskeleton developers to have a better understanding of the special challenges and needs in healthcare settings, this review discussed the most affected body regions of workers and high-risk movements during patient handling tasks, as well as the potential needs and design ideas of different types of exoskeletons including whole-body exoskeletons and exoskeletons for patients (Table 3).

One of the biggest challenges for developing ergonomic interventions for healthcare workers is the complexity of their daily tasks. Multiple joints and body parts are affected during patient handling tasks. The frequently affected body parts in work-related MSDs of nursing assistants were the back (associated with 53% of MSDs), the shoulder (13%), the leg (6%) and the arm (3%) (BLS 2018b). Unsurprisingly, in an experimental and modeling study, where the hand forces and low-back compression forces were measured and calculated during four repositioning tasks (i.e., boosting, lateral repositioning, lateral transfer and turning), both hand forces and low-back loads exceeded the recommended limits in many situations (Wiggermann et al. 2020). To design exoskeletons that could provide assistances at multiple joints and body parts, exoskeleton developers may also need to pay attention to some high-risk patient handling tasks. For example, Occupational Safety and Health Administration (OSHA) provided several examples of patient handling tasks that may be identified as high-risk movements, such as transferring from toilet to chair, transferring from chair to bed, transferring from bathtub to chair, repositioning from side to side in bed, lifting a patient in bed, repositioning a patient in chair, or making a bed with a patient in it (OSHA 2021). Additionally, lifting a patient from sitting to standing and repositioning a patient posteriorly in a wheelchair were classified as high-risk tasks for the low back from a biomechanical modeling study (Skotte et al., 2002) in which the low-back loading conditions were estimated in nine patient-handling tasks including turning, lifting, and repositioning.

Depending on the availability and accessibility of other patient handling equipment, assistance levels and types of exoskeletons may differ. There might be a demand for light “daily-use” exoskeletons or strong “task-specific ” exoskeletons. If SPHM devices, such as mechanical lift equipment, can be used while performing high-risk tasks, exoskeletons may be able to assist healthcare workers with medium- or low-risk tasks. This type of exoskeletons (e.g., artificial muscle suit or powered clothing) are expected to provide combined assistances for multiple major joints and body parts at medium or low levels, and to be worn under or over users’ medical scrubs or gowns comfortably daily. There are also several scenarios that strong “task-specific ” exoskeletons are in demand. For example, healthcare workers in surgery waiting rooms mainly perform horizontal pulling and pushing using the height-adjustable hospital bed and other assistive devices (e.g., sliding board) (Tröster et al., 2020). Exoskeletons specifically designed to provide strong assistance to manual pulling and pushing are needed. For scenarios where there is limited or no available patient handling equipment, exoskeletons are expected to provide strong and combined assistance at multiple body regions. This type of exoskeletons may be expected to be worn above the user’s medical uniform and be able to be donned and doffed quickly with minimal interference with other non-task activities. The workers may be able to choose different modules or combinations for different types of tasks.

Nevertheless, expectations for a healthcare whole-body exoskeleton are raised quite high by futuristic science fiction and movies—a “Baymax”-version exoskeleton that is powerful, but safe, and even lovable, may sound ideal (Trimboli 2014). Continuous progress is being made towards developing whole-body exoskeletons to help carry or lift patients (Ishii, Yamamoto, K., and Hyodo 2005; Yoshimitsu and Yamamoto 2004). A powered full-body exoskeleton controlled by user’s movement intention was developed and reported to provide up to 40-kg (88 lbs.) of lifting assistance. The exoskeleton was also tested in the patient handling setting (Taal and Sankai 2011), however the exoskeleton product is not yet commercially available. Despite the bulky appearance, a battery-powered full-body industrial exoskeleton was reported to be able to empower the user to lift and manipulate up to 90 kg (200 lbs.) (Sarcos 2020). It seems that we may still have a long way to go to have a powerful whole-body exoskeleton that can help lifting a patient, let alone to handle a bariatric patient. However, as technology advances and evolves, we expect to see future exoskeletons become lighter, stronger, and smarter.

Last but not least, based on the hierarchy of hazard controls (NIOSH 2015), the most effective approach of reducing, or even eliminating, MSD hazards to our workers is to remove the hazard, which is more effective than the personal protective equipment (PPE) approach (e.g., protect our healthcare worker by wearing exoskeletons). SPHM programs have taken on more effective approaches, which aim to remove MSD hazards by use of engineering controls (e.g., mechanical lifts, etc.). Similarly, healthcare workers may be protected from or less exposed to MSD risks, if there are exoskeletons designed to be worn by patients directly, which can take over tasks that are physical demanding for healthcare workers while they help patients during their treatment and rehabilitation procedures. It would be ideal for healthcare workers to only provide minimal operational or technical assistance with limited or no manual handling of the patients. For example, apart from a mechanical lift option, innovative exoskeletons could be used to help patients (even bariatric patients) reposition in the bed, sit up from the bed, or perform gait training with fall protection. Although it does not seem practical with the current wearable-robot technology, a number of promising rehabilitation exoskeletons shed light on this ultimate goal (Owens et al., 2020; Bertani et al., 2017; Louie et al., 2020). When more advanced exoskeletons are invented for patients to assist them during treatment and rehabilitation, the job for future healthcare workers may transition to helping set up and monitor patients' exoskeletons while accompanying patients.

6. Discussion and summary

As the exoskeleton technology is rapidly emerging, this review may not exhaust all applications and roles that exoskeletons could play in patient handling. Nevertheless, we want to emphasize that innovative exoskeletons and "smart" assitive devices are in great demand to help reduce work-related MSDs in healthcare workers, as well as to enhance safety and quality of care for patients.

Special features and requirements need to be considered while designing exoskeletons for healthcare workers to wear during patient handling. Unlike other male-dominated industries, the majority of the healthcare workforce are female workers. Exoskeletons for healthcare workers should be required to fit females statically, dynamically, and cognitively (Stirling et al., 2020). Besides the functionality of the exoskeleton, other aspects of human-centered care work need to be taken into consideration when designing and implementing exoskeletons in the healthcare context, particularly the social-psychological effects, when using exoskeletons with patients (Turja et al., 2020). For example, nurses' intentions to use the exoskeletons are mostly associated with perceived usefulness, ease of use, and enjoyment of use. Nurses are concerned about their own safety when wearing the exoskeleton, because the patients could grab onto the device, especially in caring for patients with dementia. Additionally, nurses' appearance may potentially resemble robots in their patients' eyes, possibly jeopardizing the delicate interaction and trust between the caregiver and the patient. These concerns need to be addressed when developing innovative exoskeletons for healthcare workers. There are additional challenges anticipated for exoskeleton applications in a healthcare setting, including but not limited to unique "object-handling" tasks (e.g., versatile task demands including the ability to react quickly to sudden situations), patient comfort and safety, limited workspaces with various medical equipment, and easy disinfection (Zheng 2020).

Like any new technology, benefits and limitations of exoskeletons need to be assessed carefully before being introduced into the field. International standards are emerging to provide guides for evaluations of industrial exoskeletons and other relevant issues (Lowe et al. 2019; ASTM 2020a, 2021a, 2021b). In the aforementioned applications using commercialized back and upper-body exoskeletons, most of the studies only evaluated the effects of exoskeleton for patient handling tasks by users' subjective perceptions (Table 1). Objective and more comprehensive evaluation approaches are needed. Both psychological (e.g., surveys and questionnaires) and physiological responses (e.g., muscle activity, oxygenation, heart dynamics, metabolic cost, etc.) of the exoskeleton users should be investigated while performing patient handling tasks and compared to no-exoskeleton conditions. Additionally, the effects of exoskeletons on the pressure or "load" at users' joints —which are not practical to measure directly—should be examined using biomechanical models. More importantly, perceptions from both healthcare workers and patients in more robust field studies are crucial to assess the efficacy of exoskeletons (O'Connor 2021).

In summary, exoskeletons are not expected to replace existing SPHM programs, but rather complement or get integrated into the programs. We expect that emerging exoskeleton products can be introduced to uncontrolled or specialized healthcare environments. There are various expectations and requirements for an exoskeleton used for different healthcare settings. Additionally, introducing certain types of exoskeletons directly applied to patients during their treatment and rehabilitation with minimal handling demand, may not only provide a new option to their recovery, but also reduce the MSD risks to the healthcare workers.

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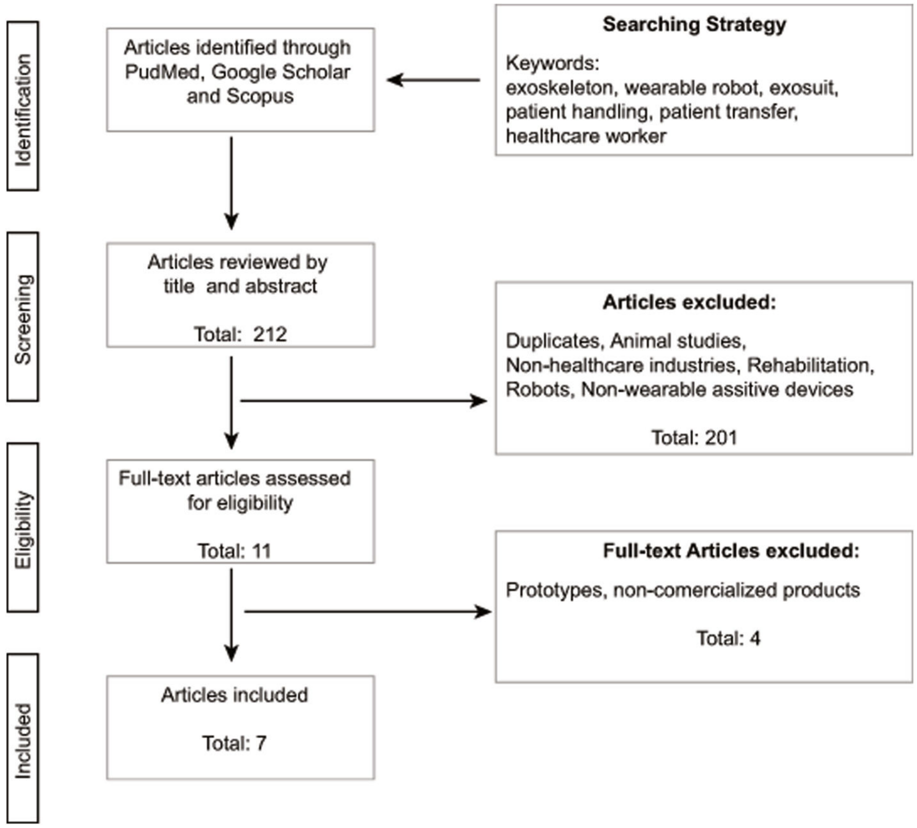

Fig. 1.
Flowchart of the article selection process.

Table 1

The overview of studies investigating commercialized exoskeleton products in patient handling.

Author, Year	Exoskeletons	Subjects	Tasks	Evaluation Methods	Results
Hwang et al., 2021	Passive back-assist exoskeletons (Flx ErgoSkeleton, V22 ErgoSkeleton, Laevo)	20 professional caregivers (17 females, 3 males)	Transfered a simulated patient (male, 84 kg) between a wheelchair and a bed with three different patient transfer methods including the squat pivot, stand pivot, and scoot with two directions (wheelchair to bed and vice versa).	Muscle activity and kinematics	The muscle activities of the erector spinae were significantly lower (up to 11.2%) with the FLx and V22 ErgoSkeletons compared to no exoskeleton condition. However, the trunk and shoulder flexion angles with the passive exoskeleton use were greater (up to 77.3%) than those without the exoskeletons.
Settembre et al., 2020	Passive back-assist exoskeleton (Laevo)	2 prone-positioning team members (Intensive care unit staff)	Performed prone-positioning procedure on a 100-kg manikin	Questionnaire on perceived efforts and torso angles	Reduced perceived efforts; minimal effects of the exoskeleton on the movement pattern
Turja et al., 2020	Passive back-assist exoskeleton (Laevo)	**Study 1:** 16 nurses and nurse students; **Study 2:** 7 nurses	**Study 1:** The nurses were paired up and tasked with assisting a geriatric patient from a hospital bed into a wheelchair. **Study 2:** The nurses deployed the exoskeleton in authentic care home environments for a week and performed tasks such as assisting a patient out and into a wheelchair, eating, and toileting.	**Study 1:** Video, interview, and survey data were collected. We analyze the survey data through descriptive statistics, which we use as a base for the qualitative analysis. **Study 2:** the nurses were interviewed before and after the trial period. The interviews were audio-recorded, transcribed, and analyzed by content analysis.	**Study 1:** Most nurses reported that the exoskeleton reduced lower back strain when assisting the patient. However, only half of the nurses reported intention to use exoskeletons in their work. **Study 2:** Mixed comments were received from patients and their colleagues regarding to the impact of social environment. Most negativity was aimed at the exoskeleton itself (e.g., appearance and ergonomics), not at the nurse wearing it.
Miura et al., 2021	Powered back-assist exoskeleton (HAL for Care Support)	19 subjects (16 men, 3 women)	Lifted a 60-kg manikin from a seated position to a standing position with and without wearing the exoskeleton.	Transfer performance; the visual analog scale (VAS) score for lumbar fatigue; muscle activity of trunk and hip muscles (on 8 subjects)	Two male and two female subjects succeeded with the exoskeleton even though they were unable to perform the task without it. Subjective lumbar fatigue during the transfer decreased significantly with using the exoskeleton: the mean lumbar fatigue VAS scores were 62 mm vs. 43 mm for without vs. with wearing the exoskeleton. The activity of the left gluteus maximus alone increased significantly with wearing the exoskeleton.
Cha et al., 2020	Passive shoulder-assist exoskeleton (Levitate AirFrame)	17 subjects (7 surgical residents, 4 surgical nurses, 3 attending surgeons)	Performed simulated surgical task: Fundamentals of Laparoscopic Surgery (FLS) peg transfer task	Usability questionnaire	The mean participant responses from the system usability scale were 81.3 out of 100, which was in the acceptable range of usability. Participants noted that exoskeletons would benefit workers who stand in prolonged, static postures (e.g., holding instruments for visualization).
Liu et al., 2018	Passive shoulder-assist exoskeleton (Levitate AirFrame)	20 surgeon subjects	Phase 1: tested for subject’s manual dexterity using the Minnesota Dexterity test, the Purdue Pegboard test, and the FLS modules; Phase 2: operated the laparoscopic camera; Phase 3: rated surgeon experience in the operating room between case-matched operating days.	Questionnaire on perceived pain and fatigue	Surgeons had the similar dexterity scores and FLS times whether or not they wore the exosuit. Exosuit surgeons experienced significantly less fatigue at all time periods and arm pain at 10 min. Surgeons wearing the exosuit during an operation experienced significant decrease in shoulder pain and 85% of surgeons reported some form of pain reduction at the end of the operative day.

Table 2

The overview of current and potential uses of existing exoskeletons.

	Existing Exoskeletons	Example Applications
Current Uses	Back-assist exoskeletons	In hospital settings - Wheelchair-to-bed patient transfer (Hwang et al., 2021) - Prone-positioning procedure (Settembre et al., 2020) - Geriatric care, e.g., wheelchair transfer, eating and toileting (Turja et al., 2020) - Lift a 60-kg patient mannequin from seating to standing (Miura et al., 2021)
	Shoulder-assist exoskeletons	In operation room settings - Static/quasi-static laparoscopy operation procedure (Cha et al., 2020; Liu et al., 2018)
Potential Uses	Back-assist exoskeletons	In homecare settings - Dressing and bathing patient, patient transfer/reposition (in bed or wheelchair) without or with limited assistive equipment In rehabilitation settings - Assisting with patient transfers and repositioning in bed - Help patients perform specific exercises repetitively (e.g., bending down to help with gait training) - Moving/lifting heavy training equipment
	Shoulder-assist exoskeletons	In rehabilitation settings - Holding patient's body part or heavy equipment (e.g., upper-body training)

Table 3

Example applications and potential features/requirements of future exoskeletons.

	Example Applications	Potential Features/Requirements
Exoskeletons for healthcare workers		
Light “daily” exoskeleton	Use for less physically demanding daily tasks - Provide gentle but constant support for multiple body regions throughout the day - May be used with other SPHM assistive devices	May wear under the medical uniform/scrub - Does not interfere with other medical devices
Strong “task- specific” exoskeleton	Use for specific tasks - Upper-body exoskeletons that mainly aid in pulling/pushing - Whole-body exoskeletons for lifting and moving patients	Easy to don and doff - Does not interfere with other medical devices
Exoskeletons for patients		
	Patient-worn exoskeletons during treatment and rehabilitation - Help patients reposition in bed, transfer to/from bed or wheelchair - Help patient perform rehabilitation training (e.g., gait training)	Certain risk prevention features (e.g., fall protection) - Requires minimal handling demand from healthcare staff