Manipulators And Work Positioners Used in Manual Material Handling Tasks: Their Biomechanical Efficacy and Factors Affecting Their Adoption

Eyad Mirdad, M.S.

Steven Lavender, Ph.D., CPE

Integrated Systems Engineering

The Ohio State University

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Abstract

Studies have shown a high risk of musculoskeletal injuries associated with manual material handling (MMH) tasks. This paper reviews the existing literature on different material-handling assistive devices that could potentially be used to reduce exposure to musculoskeletal disorder risk factors. This review intended to identify the biomechanical and performance evidence supporting the use of material handling devices and the factors that potentially affect their adoption. The research has shown the use of manipulator-assistive devices and work positioners to be efficacious regarding their potential for reducing the physical demands on the back and shoulder muscles during MMH tasks. Studying factors affecting the adoption of these devices seems to be an essential element that is commonly ignored. Reviewed studies showed that even when lift assist devices were available to workers, some preferred manual methods, resulting in unused assistive devices. The paper further revealed several different research opportunities and identified gaps that could be explored in future studies. This review can provide those designing work processes and workers involved in MMH tasks with an accessible resource regarding industrial material-handling devices.

Introduction

Studies have reported a high prevalence of shoulder and back pain, a high incidence rate of worker injuries, and a high number of workers' compensation claims among workers involved in manual material handling (MMH) tasks. In 2019, researchers investigated lower back pain among 2000 workers involved in MMH tasks. They found that in the United States 1 in 4 workers had suffered from low back pain for at least one week, 14% of workers had sought medical care, and 1 out of 10 workers had missed work due to back pain symptoms (Ferguson et al., 2019). A Liberty Mutual report identified MMH tasks, including lifting, pushing, pulling, holding, carrying, and throwing objects, as the leading cause of most serious workplace injuries that cost businesses around 14 billion dollars in 2017. This cost constituted nearly one-quarter of the overall direct employees' compensation claim costs (Liberty Mutual, 2020).

MMH tasks expose workers to several risk factors, such as awkward postures, forceful exertions, and repeated movements. Prolonged exposure to such factors in the workplace could result in fatigue; once this fatigue becomes persistent and not managed or treated, chances of musculoskeletal injury will increase (Adamo, Martin, & Johnson, 2002; Hosseini, Daneshmandi, Bashiri, & Sharifian, 2021; Wan, Qin, Wang, Sun, & Liu, 2017).

This paper reviews the existing literature on different material-handling assistive devices that potentially could be used to reduce exposures to musculoskeletal disorder risk factors and the likelihood of musculoskeletal injury. Specifically, this paper reviews the biomechanical evidence, the effects on work performance, and the factors that may affect the adoption of assistive devices by the affected workers.

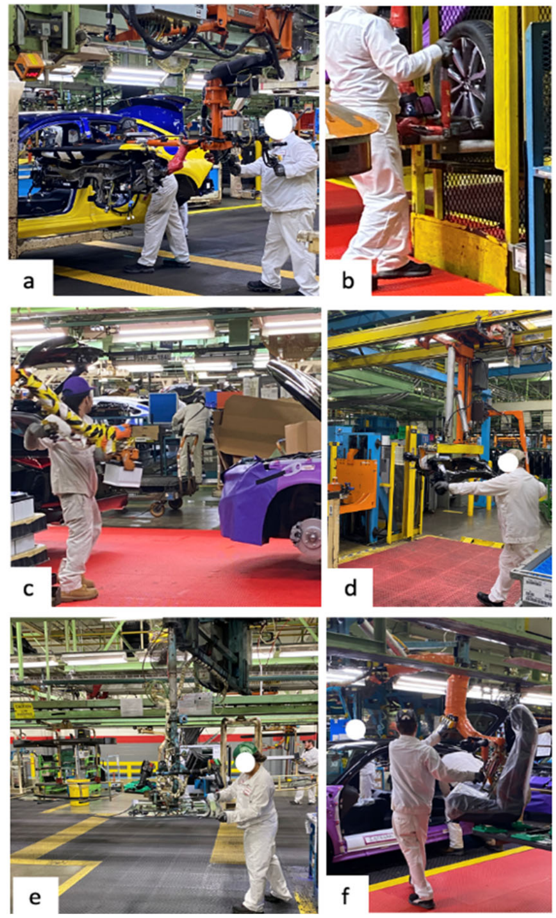

Figure 1. *Examples of manipulators being used in an automobile manufacturing facility. These manipulators are being used when (a) moving dashboard into the car, (b) installing tires, (c) installing the car's battery, (d) moving the chassis (e) preparing the windshield for installation, and (f) seat installation.*

Proposed Solutions

This paper is focused on material handling devices (MHDs) that assist workers when performing manual handling tasks by reducing a portion of the workload but do not entirely replace or automate the material handling tasks. A considerable amount of literature has been published on MHDs. Two major categories of assistive devices used in industrial MMH tasks are manipulators and positioners (Nussbaum, Chaffin, & Baker, 1999). The former category includes lift assist devices (e.g., articulated arms and hoists), while the latter includes material orientation and positioning devices (e.g., tilters and lift tables). Marras, Allread, Burr, & Fathallah (2000) studied four interventions used in MMH tasks: lift tables, manipulators, redesign, and new equipment. They found that the risk of developing back pain disorders, as determined with the lumbar motion monitor model, was significantly lower in the jobs where lift tables and manipulators were used compared to jobs without interventions. This paper reviews these two intervention categories in terms of the biomechanical evidence supporting their utility and performance.

Manipulators

The basic function of manipulators is to reduce or eliminate the weight that workers need to lift and support when lifting and/or lowering a load (Rossi, Bertoloni, Fenaroli, Marciano, & Alberti, 2013). Figure 1 shows examples of manipulators being used in industrial settings. Studies investigating these devices, listed in Table 1, have examined their use in different MMH tasks (e.g., transfer of materials, assembly operations, and palletizing). Here, the emphasis is on tasks involving short movements and light to moderate loads. Three types of manipulators appeared in the literature that fit our definition of MHDs. These include articulated arms, hoists, and intelligent assist devices. Table 1 summarizes the main results of the manipulators' studies regarding the collected biomechanical and subjective measures.

Table 1. *Studies investigating biomechanical and subjective measures manipulators.*

Author/s	Type of Study	Comparison	Task/s	Measure/s	Key Finding/s
Lu, Dufour, Weston, & Marras, 2018	Biomech-anical evaluation	Powered vacuum lifting aid versus manual handling	Airline manual baggage handling	Spine forces (compression, anterior-posterior shear, and lateral shear)	• Using a vacuum lifting aid in manual baggage handling operations significantly reduced the lumbar spinal loads compared to the manual methods.
Lavender, Ko, & Sommerich, 2013	Biomech-anical evaluation	Mobile lift assist (Eco-Pick) versus manual method	Palletizing	Lift durations, EMG from Erector Spinae, Latissimus Dorsi, Deltoid, and Bicep Muscles	• Eco-Pick significantly reduced the physical demand in four of the selected muscles compared to manual handling.
Rossi et al., 2013	Multi-criteria analysis	Intelligent assist devices versus manual methods	Lifting	Ergonomics (physical, cognitive, and organizational aspects) and performance (safety and production)	• In most of the developed criteria, the Intelligent assist device scored better than the manual method and was preferred in lifting tasks involving moderate load (20 Kg) and light loads (5 Kg). • The assisted method appeared to accommodate a much wider worker population.
Marras et al., 2000	Interventio n (before-after)	Manipulators before and after implementatio n	A wide range of MMH tasks	Low back disorder incidence rate, trunk kinematics, and lumbar motion monitor analysis.	• Manipulators significantly reduced the low back disorder incidence rate by over six injuries per 200,00 hours and the low back disorder computed risk by about 35%.
Nussbaum, Chaffin, Stump, Baker, & Foulke, 2000	Biomech-anical evaluation	Manual transfers were compared to an articulated arm and a pneumatic hoist transfer.	Transfer loads	Movement times, hand forces, trunk motions	• Hand forces during assisted transfers were substantially smaller than during manual transfers of moderate loads. • Both devices significantly decreased the relationship between mass and hand forces. • There was no apparent difference in trunk kinematics between manipulator-assisted and manual transfers. • There was a significant increase in movement time when using manipulators versus manual handling.

Author/s	Type of Study	Comparison	Task/s	Measure/s	Key Finding/s
Chaffin, Stump, Nussbaum, & Baker, 1999	Biomech-anical evaluation	The manual method was compared to an articulated arm and a pneumatic hoist	Lift or lower	Spinal forces and torso muscle antagonism from normalized EMG.	• Manipulators appeared to reduce low back compression forces significantly compared to manual handling. • A significant increase (2-4 times) appeared in torso muscle co-contraction while using manipulators-assisted compared to manual handling (lifting and lowering).
Nussbaum et al., 1999	Biomech-anical evaluation	The manual method was compared to an articulated arm and a hoist	Transfer loads	Shoulder strength capability, predicted lumbar spine forces, a metric of lumbar muscle antagonism	• Assisted transfers reduced peak shoulder and torso demands relative to the manual method. The overhead hoist was the most effective in minimizing shoulder demands. • The peak antagonistic muscle forces when using articulated arms were lower than when using the hoists. • Spine forces were decreased by 40 – 50% with the use of articulated arms or overhead hoists during transfer tasks compared to manual handling.
Nussbaum & Chaffin, 1999	Biomech-anical evaluation	The manual method was compared to an articulated arm and a hoist	Transfer loads	Effects of pacing on hand forces, torso motions, spine forces, and muscle antagonism	• When working at a self-selected speed, using MHDs resulted in lower biomechanical stresses than manual methods. • Using the articulated arms and hoists resulted in lower biomechanical stresses than the manual methods even with a pace higher than the preferred pace. However, the higher pace setting increased torso co-contraction effects, peak spine forces, and torso kinematics in both assisted and manual conditions.
Resnick & Chaffin, 1996	Biomech-anical evaluation and users' perception	Articulated arm	Push and pull	Dynamic hand forces and velocities and psychophysical variables of push and pull tasks	• Subjects with upright postures exerted peak push and pull forces around 100 N. • Peak hand velocities using an articulated arm during push and pull tasks ranged from 0.6 to 1.9 m/s. • Tasks that introduced torso twisting increased hand forces. • The subjective ratings were significantly correlated with the calculated push and pull forces, but this correlation varied considerably between subjects.
Woldstad & Chaffin, 1994	Biomech-anical evaluation	Hoist	Push and pull	Overhead carriage position and hand forces	• Subjects exerted considerable hand force levels during pushing and pulling tasks ranging from 100 N to 450 N. • The different studied task conditions did not significantly impact the applied hand forces.

Biomechanical evidence. Researchers have studied different biomechanical measures to evaluate the usage of different types of manipulators during MMH tasks. Most of the studies, listed in Table 1, have focused on the physical aspects of the MMH tasks by using objective measures, including applied forces, task performance measures such as duration, kinematic measures such as postures and movements speeds and electromyographic *(EMG)* responses. Electromyographic responses provide a measure of the muscular effort used to perform a task. EMG can also be used to assess co-contraction effects, which are when muscular forces that oppose the primary motion are generated. These co-contraction exertions are used to increase joint stability and motion accuracy. In addition, some studies have used subjective measures to assess the physical workload (e.g., perceived exertions).

In a study of an overhead rail hoist system for MMH tasks, Woldstad and Chaffin (1994) studied how the weight of the load, rail friction, movement distance, and targeted area affected the dynamic hand force applied and the position of the overhead system. They reported that the overhead hoist eliminated a substantial portion of the static force used by workers to hold the object as well as vertical force required to lift and lower the load. However, subjects exerted considerable hand force levels during pushing and pulling tasks ranging from 100 N to 450 N, and the different studied task conditions did not significantly impact these pushing and pulling forces.

A follow-up study by Nussbaum et al. (2000) studied how the applied hand forces were affected by material handling method (manual vs. an articulated arm vs. an overhead hoist), task height (mid-shank, mid-thigh, elbow, and mid-chest), trial phase (initial lifting and placement), and load mass (10, 20, and 40 kg). They found that hand forces during assisted transfers were substantially smaller than during manual transfers of moderate loads, and both the articulated arm and the overhead hoist significantly decreased the relationship between mass and hand forces. They also investigated the trunk kinematics during a simulated MMH task. The results showed that task height drove the trunk kinematics; thus, there were no significant differences in trunk kinematic measures between manipulator-assisted and manual transfers.

Resnick and Chaffin (1996) studied the impact of load (0, 23, 45, and 68 kg), target size (3.8 and 5.0 cm), and joint friction within an articulated arm (0 and 25 N added) on hand force, hand velocity, and subjective perception of the exertion during symmetric pushes and pulls of an articulated arm. In this study, researchers instructed participants to work at a comfortable pace that could be maintained for eight hours. They observed that subjects with upright postures exerted peak push and pull forces that were not excessive (typically around 100 N). Tasks that introduced torso twisting increased hand forces by 20 to 30 N, and small target sizes decreased participants' hand velocity by about 5% to 10%, indicating the importance of MHDs' layout in terms of productivity. The subjective ratings were significantly correlated with the calculated push and pull forces, but this correlation varied considerably between subjects.

Several studies have estimated spinal forces using biomechanical models, used motion capture systems to collect kinematics, and investigated the activity of the back, torso, shoulder, and hand muscles using EMG for different MMH tasks using manual and manipulator-assisted methods. Nussbaum, Chaffin, and Baker (1999) examined the dynamic joint loads and EMG activities when load transfer tasks were performed using a manual approach, an overhead hoist, and an articulated arm. They found that assisted transfers reduced peak shoulder and torso muscular demands relative to those observed using the manual methods, with the overhead hoist being the most effective in minimizing shoulder demands. Spine forces were decreased by 40 to 50 percent with the use of either articulated arms or overhead hoists during transfer tasks compared to manual handling. Articulated arms were the most effective method in minimizing anterior-posterior (A/P) shear forces, while the overhead hoists were the most effective method in reducing compression forces. On the other hand, the overhead hoist increased the muscular co-contraction compared to that observed with the articulated arm and manual approach, thus indicating higher coordinative efforts. These results were confirmed by Chaffin et al. (1999), who reported that trunk muscle co-contraction effects were present, especially while using the overhead hoists. They also found from their spine modeling process, based on the EMG analysis of the low back muscles, that MHDs reduced compression forces compared to manual handling by 33 to 40 percent for the articulated arms and hoists, respectively.

Nussbaum and Chaffin (1999) studied the effect of task speed (preferred and fast) on muscles' co-contraction, spine forces, and torso kinematics using articulated arms and hoists compared to the manual method. Using the articulated arms and hoists resulted in lower biomechanical stresses than the manual methods even with a pace higher than the preferred pace. It should be noted, however, that the higher pace setting increased torso co-contraction effects, peak spine forces, and torso kinematics across all the studied conditions.

As part of their study, Marras et al. (2000) investigated whether the use of manipulators influences low back disorder incidence rates, trunk kinematics, and risk determined using the lumbar motion monitor risk model, a dynamic risk assessment method developed by Marras et al. (1993) to assess and quantify the risk of a low back injury in the workplace. They found that manipulators significantly reduced the low back disorder incidence rate by around 6 percent and the computed low back disorder risk index by about 35 percent.

Lavender et al. (2013) investigated the biomechanical efficacy Eco-pick device. This is a mobile lift assist device that can be integrated into a pallet jack for pick-to-pallet processes. When activated, the Eco-Pick applies a lifting force via straps attached to the worker's forearms, which raises the workers' arms to assist them in lifting items during palletizing or depalletizing tasks. The authors analyzed the normalized EMG signals from Erector Spinae, Latissimus Dorsi, Deltoid, and Bicep muscles as their participants transferred 16.4 kg totes from one pallet to another, simulating a warehouse selection task. They found that Eco-pick reduced the physical demands on the back and shoulder muscles during the simulated palletizing tasks. Thus, this device, which is designed to be mobile so that it can move throughout a facility, has the potential to minimize the exposure to risk factors associated with case selection work in a warehouse facility.

Likewise, Lu et al. (2018) assessed an articulated arm with a powered vacuum lifting device during simulated airline manual baggage handling tasks. The usage of this device significantly reduced the compressive spinal forces by 39% and the A/P shear forces by 25% relative to the manual methods.

Performance assessment. There is a lack of studies focusing on the usability of manipulators within the context of MMH tasks. Most studies have focused on the operator physical demands; however, some included performance measures as a dependent variable. Rossi et al. (2013) used an analytic hierarchy process, which is a decision analysis method for multiple tangible and intangible criteria, to evaluate the complex material handling environment and identify better situational approaches. The authors conducted a case study to assess their proposed hierarchy, comparing manual methods and an advanced class of articulated arms with a computer-controlled servo during lifting tasks. These devices with servo are known as intelligent assist devices as they provide power assistance and motion guidance. The overall result indicated that the intelligent assist device had a better score on task performance measures, including productivity, adaptability, capability, and flexibility, than the manual method and was preferred in lifting tasks involving moderate loads (20 Kg) and light loads (5 Kg) with respect to most of the developed criteria. Moreover, the use of the intelligent assist devices appeared to accommodate a much wider worker population.

Some studies assessed performance during MMH tasks by measuring task duration, movement time, and travel distance. Resnick and Chaffin (1997) found that the articulated arm decreased movement time and distance relative to that observed with the overhead rail hoist. Nussbaum et al. (2000) found a significant increase in movement time when using manipulators. Relative to manual handling, movement times were about 40% longer when using a pneumatically articulated arm and 75%

longer than when using an overhead hoist. However, the time delay did vary with changes in the objects' height and mass. Lavender et al. (2013), in their Eco-pick study, found that the average task duration of a task that required the transfer of three totes to a pallet was 1.1 seconds longer when using the Eco-Pick than when the manual method was used. However, in this case, while this was a statistically significant change, the 0.33 seconds per tote increase may not be of much functional significance, especially if one considers this was a short-term task that does not account for potential slowing due to fatigue that may be more likely to occur with the more manual method had the task been performed for a more typical work duration period.

In sum, manipulators can increase movement time, movement distance, and task duration. These differences depend upon the selected device, the tasks, the level of movement precision required, and the lifted objects' height and mass. However, using manipulators may not affect the overall system performance in terms of time if workers need fewer breaks and may lead to equivalent daily productivity metrics over the course of a full work the day when compared to manual methods. Future studies on the current topic are therefore recommended.

Positioners

Positioners are devices that enable workers to place or orient objects thereby making them easier to reach, pick, or stock. Figure 2 shows some examples of positioners being used in warehouses and manufacturing facilities. Studies, listed in Table 2, have investigated these devices during different MMH tasks (e.g., picking, placing, orienting, and stocking). Here, the emphasis is on devices that help workers raise and orient pallets and bins to improve access to handled materials. Table 2 summarizes the main results of the positioners' studies regarding the collected biomechanical and subjective measures.

Table 2. *Studies regarding positioners concerning biomechanical and subjective measures of their utility*

Author/s	Type of Study	Comparison	Task/s	Measure/s	Key Finding/s
Hanson, Medbo, Assaf, & Jukic, 2018; Hanson, Medbo, Berlin, & Hansson, 2018	Observational (time study and simulation)	Horizontal pallets versus tilted pallets	Picking from large containers	Physical workload (REBA) and simulation and picking time	• The use of pallet tilters improved performance in picking time, variation in time, and space efficiency • compared to horizontal pallets. • The physical workload may decrease or increase when using both flat and tilted pallets (45° tilted angle toward workers), depending on the location and components of materials.

Author/s	Type of Study	Comparison	Task/s	Measure/s	Key Finding/s
Ohu, Cho, Kim, & Lee, 2016	Biomechanical evaluation	Stocking with a height-adjustable mobile cart versus without the cart	Stocking	Normalized EMG signals from biceps, triceps, trapezius, and erector spinae muscles, muscle force metric, and performance	• The muscle force metric and the analysis of the visual observations revealed that using a mobile cart decreased ergonomics risks and increased performance (in terms of the number of stocked items, the travel distances, and the treated cases). • The use of the mobile cart reduced the EMG normalized signals by 24% in activities directly related to stocking tasks compared to the without-cart scenario.
(Davis & Orta Anés, 2014)	Biomechanical evaluation and risk assessments	High-adjustable carts versus traditional carts	Stocking	Trunk kinematics, low back disorder risk index, horizontal moment arms, subjective ratings, and NIOSH lifting index	• The adjustable cart eliminated the low-level lift and thus lessened the trunk flexion compared to the traditional flat cart. • The subjective rating of the adjustable cart exertion supported the objective measures in terms of benefits and effectiveness. • Using the adjustable cart improved performance by reducing the task duration by about 3 seconds for each task condition.
(Ramsey, Davis, Kotowski, Anderson, & Waters, 2014)	Biomechanical evaluation	A Self-leveling pallet carousel (turntable) and height adjustable cart versus pallet on the floor and flat cart	De-palletizin g	Spine forces and perceived exertion	• Self-leveling carousel and adjustable cart together produced the most effective reduction of spinal loads compared to a pallet on the floor and a flat cart. The self-leveling carousel had the highest main effect on spine forces by reducing the spinal compression and shear forces. • The use of the adjustable cart alone also decreased the spinal loads, however, to a lesser degree than the self-leveling carousel.
Ulin & Keyserling, 2004	Intervention (before-after)	Lift and tilt pallet jack before and after implementation	Stocking, picking, packing, lifting, and pulling.	Spine compression, torso and shoulder demands, kinematics, and worker perceptions	• The use of a tilter (with the 90° tilting angle toward workers) eliminated the long flat reaches and reduced biomechanical and posture demands.

Marras et al., 2000	Intervention (before-after)	Lift tables before and after implementation	A wide range of MMH tasks	Low back disorder incidence rate, trunk kinematics, and lumbar motion monitor analysis.	• Lift tables significantly reduced low back disorder incidence rate by over than seven injuries per 100 employees, forward torso bending, sideways movement velocity, and the low back disorder risk by about 18%.
Stuart-Buttle, 1995	Case study	Scissor lift workstation	Palletizin g	Lumbar motion monitor analysis	• The modified scissor lift condition (lowering the high fence of the device and removing the lip along the side of the picking area) reduced the overall low back injury risk by lowering the amount of forward torso bending and sideways movement velocity relative to floor palletizing.

Figure 2. *Different types of positioners being used in industrial setting which include (a) a scissors lift, (b) a scissors lift mounted on a cart to facilitate handling and transportation, (c) pallets on self-leveling tables to reduce forward bending in a warehouse, and (d) a tilted bin to facilitate picking.*

Biomechanical evidence. Researchers have studied different biomechanical measures to evaluate the efficacy of different types of positioners used in MMH tasks, including pallet lifts, pallet tilters, height adjustable mobile carts, and self-leveling carousels. Stuart-Buttle (1995) conducted a case study in a meat processing plant to evaluate three palletizing conditions using the lumbar motion monitor: (1) Lifts to a pallet located on the floor, (2) Lifts to a pallet on a scissor lift workplace which included a high rail around the scissor lift and a raised lip along the side of the picking area, and (3) lifts to a pallet on a modified scissor lift table that had a lower rail and the lip alongside removed. The author found that the scissor lift condition exposed the subject to a higher risk than the floor palletizing condition due to the mentioned barriers. The modified situation reduced the overall low back injury risk by lowering forward torso bending and sideways movement velocity relative to floor palletizing. These results were confirmed by Marras et al. (2000), who found that lift tables significantly impacted forward torso bending and sideways movement velocity, which in turn reduced the normalized low back disorder incidence rate by about 7 percent and the low back disorder risk by about 18 percent.

Ulin and Keyserling (2004) conducted before-and-after case studies to assess worker's spine compression, torso and shoulder demands, and postures pre and post the implementation of a lift/tilt pallet jack. This device raises and tilts pallets loaded with tri-walls bin. It was found that the lift/tilt pallet jack eliminated the long flat reaches and reduced biomechanical and posture demands. The maximum ergonomics benefit of the lift/tilt pallet jack appeared with the 90° tilting angle toward workers, as moderate tilting angles using this device seemed to increase the horizontal reach distances due to built-in obstructions in the lift/tilt device hardware. Regarding moderate tilting angles, two parallel studies (Hanson, Medbo, Assaf, et al., 2018; Hanson, Medbo, Berlin, et al., 2018) indicated that the physical workload might decrease or increase when using both flat and tilted pallets loaded with containers (45° tilted angle toward workers), depending on the location of the materials and whether the materials can slide toward the worker (i.e., picking items from the far end of pallets may put workers at risk).

Ramsey et al. (2014) studied how the spine loads and the subjective ratings of exertion were affected by having adjustable heights at the lift origin, the lift destination, or at both the origin and destination. More specifically, they compared lifts from a pallet on the floor or from a self-adjusting lift-table with a carousel top (a.k.a. turntable). The lifted items were either placed on a traditional flatbed cart or a cart with a self-adjusting lift-table. At both the origin and the destination, the self-adjusting heights were approximately hip level. The results showed that the self-leveling carousel and lift-table cart together produced the most effective reduction of spinal loads compared to the traditional de-palletizing task (pallet on the floor and a traditional flat cart). Individually, the self-leveling carousel had the highest main effect on spine forces by reducing the three spinal loading variables (compression, anterior-posterior shear, and lateral shear). The use of the lift-table cart alone also decreased the spinal loads, but to a less degree than the self-leveling carousel when compared to the traditional task.

Another study on the mobile cart by Davis and Orta Anés (2014) compared a traditional flatbed cart to a self-adjustable height cart, which maintains products at mid-thigh level during stocking tasks. The study examined how kinematics, risk assessment indicators (i.e. low back disorder risk index and the NIOSH lifting index), subjective exertion ratings, and task durations vary when using these carts in different situations. The adjustable cart eliminated the low-level lifting, thus reducing the trunk flexion observed when working with the traditional flat cart. This reduction in trunk flexion would have the potential to reduce musculoskeletal risk. The use of the adjustable cart slightly decreased low back disorder and NIOSH lifting indexes. However, the adjustable cart had exposed subjects to a higher trunk twisting motion than the traditional cart, which might be partially due to the big size of the adjustable cart relative to the traditional cart used in the study. This result suggests that it is important to also consider where carts are placed relative to the lift's origin or destination as this placement may have a significant impact on twisting motions. For example, Kim al. (2014) and Mehta et al. (2014) found twisting motions were reduced when the lift's origin and destination were separated by 1 to 1.25 meters when palletizing and depalletizing. It is also worth noting that the subjective ratings of the exertion supported the objective measures in terms of benefits and effectiveness of the self-adjusting carts.

Ohu et al. (2016) studied how the normalized EMG signals collected bilaterally from the biceps, triceps, trapezius, and erector spinae were affected when stocking grocery shelves when (1) using an adjustable height mobile cart; and (2) when using the traditional method wherein boxes are placed on the floor or held in place using the lower extremities. The use of the mobile cart reduced the EMG normalized signals by about 25 percent in activities directly related to stocking tasks (value-added activities) relative to the without-cart scenario.

Performance assessments. The literature search identified few studies that have investigated the overall work performance changes due to positioners in terms of productivity. Davis and Orta Anés (2014) indicated that using the adjustable cart improved performance by reducing the duration of lifting task conditions (six-packs of 2-liter beverage bottles, 12 boxes of soup cans, six bags of dog food, and unloading pairs of 12-packs of beverage products onto the shelf) by about 3 seconds for each task condition. This results were confirmed by Ohu et al. (2016), who showed from the analysis of the visual observations that using a mobile cart improved stocking grocery shelves task performance by increasing the number of stocked items on shelves and reducing the travel distances relative to the without cart scenario.

Two observational studies in an automotive assembly plant by (Hanson, Medbo, Assaf, et al., 2018; Hanson, Medbo, Berlin, et al., 2018) have compared the picking times of different components (oil filters, brackets, ducts, engine mounts, and pipes) with weights ranging from 1.2 kg to 7.9 kg when using tilted pallets loaded with containers relative to flat containers. Both studies showed that using pallet tilters significantly reduced average picking time of all studied parts by about 45 percent, decreased the variation in time, and improved space efficiency compared to flat containers.

Adoption of Ergonomic Equipment

Ergonomic interventions such as the manipulators and positioners are often introduced to reduce the incidence of MSD. While ergonomic interventions, such as manipulators and positioners, have been shown in the previous sections of this paper to be efficacious in reducing biomechanical loading, the success of implementation and the adoption by the intended users still remains a challenge (Dale et al., 2017; Weinstein, Hecker, Hess, & Kincl, 2007; Yazdani & Wells, 2018; Zare, Black, Sagot, Hunault, & Roquelaure, 2020). In the context of industrial MMH, even when lift assist devices were available to workers, some workers continue to use manual methods rather than mechanized assist devices, resulting in assistive devices being pushed aside (Nussbaum et al., 2000; Nussbaum & Chaffin, 1999; Woldstad & Chaffin, 1994). Our review of the literature found very few papers focusing on the factors affecting the adoption of assistive devices in industrial settings. On the other hand, there are significantly more studies investigating the factors affecting assistive device adoption in healthcare settings (patient handling). These studies can provide beneficial insights regarding the adoption of MMH aids within industrial tasks.

Factors affecting adoption

To further the successful adoption of ergonomic solutions, prior studies have investigated the role of barriers and facilitators in the intervention adoption process. Figure 3 summarizes factors at both the organizational and individual levels affecting adoption of assistive devices that will be discussed in more details in the following sections.

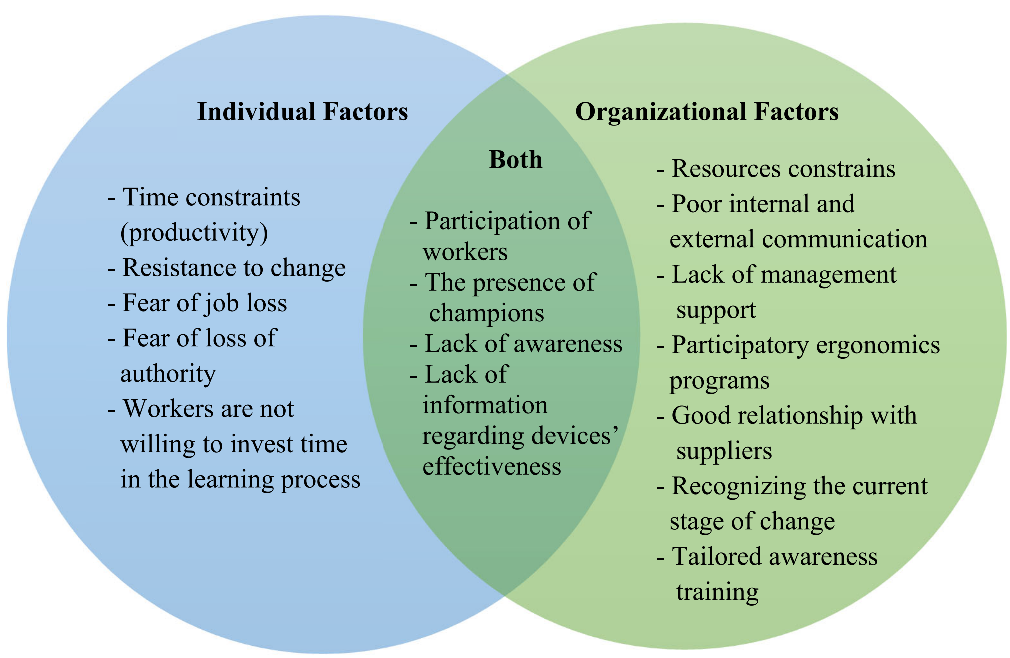

Figure 3. *Individual and organizational factors identified in the literature that may affect adoption of assistive devices in industrial settings.*

Barriers. In the ergonomics intervention literature, barriers are defined as factors that inhibit the adoption of specific ergonomic changes in a work process. Barriers can exist at both the organizational level and at the level of the actual users. Organizational level barriers often include operational costs, maintenance concerns, and possible negative effects on overall productivity. Assuming these are addressed prior to implementation, barriers often exist from the perspective of the individual users. Thus, even if a specific ergonomic intervention showed its efficacy through an ergonomic evaluation in terms of reducing workplace hazards, many workers are still skeptical about using or adopting these interventions due to specific barriers (Dale et al., 2017; Weiler et al., 2013). Yazdani & Wells (2018) identified in their review both organizational and individual factors that could inhibit the implementation of interventions. Factors at the organizational level includes: (a) resources constraints (e.g. money, equipment, and staff), (b) communication challenges both internally (i.e., between different departments within an organization) externally, and (c) lack of management support for and commitment to the ergonomic initiatives within the facility. At the individual level, these factors include: time constraints, resistance to change; and fear of job loss or loss of authority.

In the context of MMH, some studies reported that organizational barriers affecting the adoption of assistive devices were mostly related to operating cost (time and maintenance) and lack of ergonomics guidance, while individual barriers were in most cases related to productivity (time pressure) and lack of information regarding devices' effectiveness (Nussbaum et al., 2000; Nussbaum & Chaffin, 1999; Woldstad & Chaffin, 1994). While Nussbaum et al. (1999) expected a decrease in motion times while using manipulators with more practice, and the old adage "practice makes perfect" likely applies, many workers are not willing to invest time in the learning process. The data suggest that as this learning process progresses, the initial increase in physical stress when using the assistive devices, for example due to muscle co-contraction, would be reduced as skilled usage behaviors develop.

Facilitators. Removing the barriers alone is not significant in adopting interventions (Weiler et al., 2012). It is also important to focus on facilitators of intervention adoption. Yazdani & Wells (2018) suggested in their review the following organizational factors that could lead to successful implementations of interventions aimed at preventing MSDs: a) Communications that create the perception within the organization that the interventions are a long-term commitment to both safety and success, b) Involvement of ergonomists throughout the implementation phase and training, c) Incorporation of human factors principles into the continuous improvement processes, d) Positive and strong communication between employees, supervisors, and management, and e) Involvement of workers (end users) within the implementation and development of changes. In addition, Schwerha et al. (2021) indicated that a good relationship with suppliers was one of the factors that facilitated the adoption of new assistive devices.

Burgess-Limerick's (2018) review article emphasized the importance of using a participatory ergonomics process as the use of this macro-ergonomics technique is believed to result in greater adoption of changes. In the context of industrial MMH, Gajšek et al. (2020) demonstrated the importance of workers' participation in the selection processes of assistive devices. Workers who participated in the selection processes of transport aids reported significantly fewer perceived health problems, such as fewer incidents of leg and wrists pain and less mental fatigue. Mack et al. (1995), in their study of industrial MMH aids, demonstrated the importance of users views on device usability, especially their perceptions regarding ease of use and acceptability of devices. Zare et al. (2020) demonstrated that reduced occupational exposure to physical risk factors was achieved by not only considering a combination of engineering interventions and organizational interventions, but also through stakeholder involvement.

Apart from that, researchers have approached other ways that might help in successful ergonomic changes adoption by using health behavior and social theories such as innovation diffusion theory, the health belief model, and the transtheoretical model (Dale et al., 2017; Park, Lavender, Sommerich, & Patterson, 2018; Prochaska, Diclemente, & Norcross, 1993; Weiler et al., 2013; Weinstein et al., 2007). Innovation Diffusion Theory, introduced by Rogers (1995), focussed on how people adopt new behaviors, ideas or products. In the literature, the presence of champions, who are defined as change agents in Rogers' theory, was one important facilitator. In fact, endorsement by champions has been identified by several authors as a facilitating factor that enhances the adoption ergonomic solutions. (Burgess-Limerick, 2018; Dale et al., 2017; Santos, Graham, Lalonde, Demery Varin, & Squires, 2022; Weiler et al., 2013). Weiler and colleagues (2012), in their study on EMS personnel, tried to determine what factors affect the intention to use transfer-board intervention and the adoption of this solution. They found out that perceived ergonomics advantage was strongly correlated to intention to use. However, the presence of site champions was also influential in the adoption of the folding slide board. Those champions could be anyone in the institution promoting lift assist use, but the most effective champions are co-workers. Thus, identifying individuals within the workforce that have a positive attitude about the implementation of equipment such as manipulators and positioners could facilitate their use by others in the workforce.

The Transtheoretical Model or the Stages of Change theory is another behavior theory suggesting that people move through the following sequence of stages when thinking of changing behavior: (1) pre-contemplation, (2) contemplation, (3) preparation, (4) action, and (5) maintenance (Prochaska et al., 1993). They found that knowing when the change occurs and at which stage individuals are in is crucial to providing support for the appropriate intervention as it moves through the stages of change process. Park et al. (2018), in their study on lifting devices used in nursing homes, revealed that participants' responses to facilitators and barriers to adopting lifting device intervention were different depending on the individual’s adoption stage (Park et al., 2018). Therefore, it is essential to realize that when implementing an intervention, the current stage of the targeted individuals when developing plans to facilitate the adoption of ergonomic changes (Park et al., 2018; Prochaska et al., 1993).

Research has also provided evidence that ergonomic awareness training helps facilitate adoption (Madhwani & Nag, 2019). Gajšek et al. (2020) demonstrated that order pickers who had been educated in ergonomics reported significantly less perceived upper and lower extremities pain. In addition, Nussbaum et al. (2000) considered the lack of ergonomics guidance as one of the reasons why workers did not adopt manipulators even if they were available. Park et al. (2018), in their nursing homes lifting devices study, recommended that further studies should be dedicated to creating an *assessment instrument* that classifies targeted worker based on their stage of change, which can then be used to create tailored awareness training programs that facilitate movement to the next stage of the adoption process (Park et al., 2018).

In summary, the research has identified several factors that help facilitate intervention adoption. Those factors include proper training, effective communication, transparent implementation, and tailored awareness training. It is critical to realize that a comprehensive framework incorporating health behavior, innovation, adoption, management, and ergonomics is essential to implement, adopt, and maintain ergonomic changes successfully.

Research opportunities

This paper revealed several different research opportunities that could be explored:

1. There is a need to assess the usability of different MHDs in terms of operators’ mental workload.
2. There is a need to update the studies on industrial manipulators, which were conducted approximately 20 years ago. Therefore, studies are needed for the

current devices, including intelligent assist devices, regarding their effect on operator physical demands.

3. There is a need to build on the adoption studies that have focused on assistive devices used in patient handling, further intervention adoption studies are needed with a specific focus on industrial solutions.
4. There is a need to understand how people effectively learn to use industrial manipulators and the duration of the learning process upon the completion of which users are highly proficient with the device. By quantifying the long-term and short-term learning effects on biomechanical measures, and overall system performance reasonable expectations can be developed as to operators' performance as they begin using industrial manipulators.

Conclusions

The purpose of this review was to identify the biomechanical and performance evidence supporting the use of material handling devices and the factors potentially affecting their adoption. The research has shown the use of manipulator-assistive devices to be efficacious with regards to their potential for reducing the physical demands on the back and shoulder muscles during MMH tasks. On the other hand, manipulators appeared to increase movement time, movement distance, and task duration. However, many of these studies were short term laboratory studies that did not allow participants to become highly skilled while using the manipulators. Moreover, it is likely that overall system performance would not be negatively affected as workers may be less fatigued and there take fewer breaks, which in turn may maintain consistent task performance rates through the workday.

Most of the studied positioners (e.g., Self-leveling pallets, turntables, and height-adjustable carts) showed their effectiveness during MMH tasks. When selecting an aid, it is important to consider the task requirements (e.g., speed of work and availability of assistance) and environmental conditions (e.g., lighting, surface friction, and slopes or ramps), in addition to the space constraints and work layout.

Studying factors affecting the Adoption of MHDs seems to be an essential element that is commonly ignored. Reviewed studies showed even when lift assist devices were available to workers, there are workers who tended to preferer manual methods, resulting in unused assistive devices. It is important that organizations consider the different facilitators and barriers discussed above when planning an implementation of MHDs.

The findings in this review are subject to some limitations. First, the sample articles of this review was limited to peer review journals articles. Second, this review was limited to assistive devices used in MMH tasks that deal with bins and pallets and involve short movement and light to moderate mass, excluding crane systems.

Although the current review is based on a limited sample of articles, this paper can provide those designing work processes and workers involved in MMH tasks an accessible resource regarding industrial material-handling devices in terms of biomechanical evidence and performance. This paper also highlights the features of those devices and the factors that need to be considered during implementation which ultimately affect their adoption.

References

Adamo, D. E., Martin, B. J., & Johnson, P. W. (2002). Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury. *European Journal of Applied Physiology*, *88*(1–2), 134–140. https://doi.org/10.1007/s00421-002-0660-y

Burgess-Limerick, R. (2018). Participatory ergonomics: Evidence and implementation lessons. *Applied Ergonomics*, *68*(December 2017), 289–293. https://doi.org/10.1016/j.apergo.2017.12.009

Chaffin, D. B., Stump, B. S., Nussbaum, M. A., & Baker, G. (1999). Low-back stresses when learning to use a materials handling device. *Ergonomics*, *42*(1). https://doi.org/10.1080/001401399185829

Dale, A. M., Jaegers, L., Welch, L., Barnidge, E., Weaver, N., & Evanoff, B. A. (2017). Facilitators and barriers to the adoption of ergonomic solutions in construction. *American Journal of Industrial Medicine*, *60*(3), 295–305. https://doi.org/10.1002/ajim.22693

Davis, K. G., & Orta Anés, L. (2014). Potential of adjustable height carts in reducing the risk of low back injury in grocery stockers. *Applied Ergonomics*, *45*(2 PB). https://doi.org/10.1016/j.apergo.2013.04.010

Ferguson, S. A., Merryweather, A., Thiese, M. S., Hegmann, K. T., Lu, M. L., Kapellusch, J. M., & Marras, W. S. (2019). Prevalence of low back pain, seeking medical care, and lost time due to low back pain among manual material handling workers in the United States. *BMC Musculoskeletal Disorders*, *20*(1). https://doi.org/10.1186/s12891-019-2594-0

Gajšek, B., Dukić, G., Butlewski, M., Opetuk, T., Cajner, H., & Kač, S. M. (2020). The impact of the applied technology on health and productivity in manual “picker-to-part” systems. *Work*, *65*(3). https://doi.org/10.3233/WOR-203107

Hanson, R., Medbo, L., Assaf, M., & Jukic, P. (2018). Time efficiency and physical workload in manual picking from large containers. *International Journal of Production Research*, *56*(3). https://doi.org/10.1080/00207543.2017.1371352

Hanson, R., Medbo, L., Berlin, C., & Hansson, J. (2018). Manual picking from flat and tilted pallet containers. *International Journal of Industrial Ergonomics*, *64*. https://doi.org/10.1016/j.ergon.2017.07.001

Hosseini, E., Daneshmandi, H., Bashiri, A., & Sharifian, R. (2021). Work-related musculoskeletal symptoms among Iranian nurses and their relationship with fatigue: a cross-sectional study. *BMC Musculoskeletal Disorders*, *22*(1). https://doi.org/10.1186/s12891-021-04510-3

Kim, T.H., Mehta, J.P., Weiler, M.R., Lavender, S.A. (2014). The effects of transfer distance on spine kinematics when placing boxes at different heights Applied Ergonomics, 45, 936-942.

Lavender, S. A., Ko, P. L., & Sommerich, C. M. (2013). Biomechanical evaluation of the Eco-Pick lift assist: A device designed to facilitate product selection tasks in distribution centers. *Applied Ergonomics*, *44*(2), 230–236. https://doi.org/10.1016/j.apergo.2012.07.006

Lu, M. L., Dufour, J. S., Weston, E. B., & Marras, W. S. (2018). Effectiveness of a vacuum lifting system in reducing spinal load during airline baggage handling. *Applied Ergonomics*, *70*. https://doi.org/10.1016/j.apergo.2018.03.006

Mack, K., Haslegrave, C. M., & Gray, M. I. (1995). Usability of manual handling aids for transporting materials. *Applied Ergonomics*, *26*(5). https://doi.org/10.1016/0003-6870(95)00056-9

Madhwani, K. P., & Nag, P. K. (2019). Effective Office Ergonomics Awareness: Experiences from Global Corporates. *Indian Journal of Occupational and Environmental Medicine*, *21*(2), 77–83. https://doi.org/10.4103/ijoem.IJOEM_151_17

Marras, W. S., Allread, W. G., Burr, D. L., & Fathallah, F. A. (2000). Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks. *Ergonomics*, *43*(11). https://doi.org/10.1080/00140130050174518

Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A., & Ferguson, S. A. (1993). The Role of Dynamic Three-Dimensional Trunk Motion in Occupationally-Related Low Back Disorders. *Spine*, *18*(5). https://doi.org/10.1097/00007632-199304000-00015

Mehta, J.P., Kim, T.H., Weiler, M.R., Lavender, S.A. (2014). Effects of transfer distance on spine kinematics for de-palletizing tasks. Journal of Occupational and Environmental Hygiene, 11, 1-8.

Nussbaum, M. A., & Chaffin, D. B. (1999). Effects of pacing when using material handling manipulators. *Human Factors*, *41*(2). https://doi.org/10.1518/001872099779591240

Nussbaum, M. A., Chaffin, D. B., & Baker, G. (1999). Biomechanical analysis of materials handling manipulators in short distance transfers of moderate mass objects: Joint strength, spine forces and muscular antagonism. *Ergonomics*, *42*(12). https://doi.org/10.1080/001401399184703

Nussbaum, M. A., Chaffin, D. B., Stump, B. S., Baker, G., & Foulke, J. (2000). Motion times, hand forces, and trunk kinematics when using material handling manipulators in short-distance transfers of moderate mass objects. *Applied Ergonomics*, *31*(3). https://doi.org/10.1016/S0003-6870(99)00062-9

Ohu, I. P. N., Cho, S., Kim, D. H., & Lee, G. H. (2016). Ergonomic Analysis of Mobile Cart-Assisted Stocking Activities Using Electromyography. *Human Factors and Ergonomics In Manufacturing*, *26*(1). https://doi.org/10.1002/hfm.20612

Park, S., Lavender, S. A., Sommerich, C. M., & Patterson, E. S. (2018). Increasing the Use of Patient Lifting Devices in Nursing Homes: Identifying the Barriers and Facilitators Affecting the Different Adoption Stages for an Ergonomics Intervention. *International Journal of Safe Patient Handling & Mobility (SPHM)*, *8*(1), 9–24. http://search.ebscohost.com/login.aspx?direct=true&db=ccm&AN=129355144&site=ehost-live

Prochaska, J. O., Diclemente, C. C., & Norcross, J. C. (1993). In search of how people change: Applications to addictive behaviors. *Journal of Addictions Nursing*, *5*(1). https://doi.org/10.3109/10884609309149692

Ramsey, T., Davis, K. G., Kotowski, S. E., Anderson, V. P., & Waters, T. (2014). Reduction of spinal loads through adjustable interventions at the origin and destination of palletizing tasks. *Human Factors*, *56*(7). https://doi.org/10.1177/0018720814528356

Resnick, M. L., & Chaffin, D. B. (1996). Kinematics, kinetics, and psychophysical perceptions in symmetric and twisting pushing and pulling tasks. *Human Factors*, *38*(1). https://doi.org/10.1518/001872096778940778

Rogers, E.M. (1995) Diffusion of Innovations. 4th Edition, the Free Press, New York.

Rossi, D., Bertoloni, E., Fenaroli, M., Marciano, F., & Alberti, M. (2013). A multi-criteria ergonomic and performance methodology for evaluating alternatives in “manuable” material handling. *International Journal of Industrial Ergonomics*, *43*(4). https://doi.org/10.1016/j.ergon.2013.04.009

Santos, W. J., Graham, I. D., Lalonde, M., Demery Varin, M., & Squires, J. E. (2022). The effectiveness of champions in implementing innovations in health care: a systematic review. *Implementation Science Communications*, *3*(1), 80. https://doi.org/10.1186/s43058-022-00315-0

Schwerha, D. J., McNamara, N., Nussbaum, M. A., & Kim, S. (2021). Adoption potential of occupational exoskeletons in diverse enterprises engaged in manufacturing tasks. *International Journal of Industrial Ergonomics*, *82*. https://doi.org/10.1016/j.ergon.2021.103103

Stuart-Buttle, C. (1995). A Case Study of Factors Influencing the Effectiveness of Scissor Lifts for Box Palletizing. *American Industrial Hygiene Association Journal*, *56*(11). https://doi.org/10.1080/15428119591016359

Ulin, S. S., & Keyserling, W. M. (2004). Case studies of ergonomic interventions in automotive parts distribution operations. *Journal of Occupational Rehabilitation*, *14*(4). https://doi.org/10.1023/B:JOOR.0000047432.07837.64

Wan, J. J., Qin, Z., Wang, P. Y., Sun, Y., & Liu, X. (2017). Muscle fatigue: General understanding and treatment. *Experimental and Molecular Medicine*, *49*(10), e384-11. https://doi.org/10.1038/emm.2017.194

Weiler, M. R., Lavender, S. A., Crawford, J. Mac, Reichelt, P. A., Conrad, K. M., & Browne, M. W. (2012). Identification of factors that affect the adoption of an ergonomic intervention among Emergency Medical Service workers. *Ergonomics*, *55*(11), 1362–1372. https://doi.org/10.1080/00140139.2012.714474

Weiler, M. R., Lavender, S. A., Crawford, J. Mac, Reichelt, P. A., Conrad, K. M., & Browne, M. W. (2013). A structural equation modelling approach to predicting adoption of a patient-handling intervention developed for EMS providers. *Ergonomics*, *56*(11), 1698–1707. https://doi.org/10.1080/00140139.2013.835075

Weinstein, M. G., Hecker, S. F., Hess, J. A., & Kincl, L. (2007). A Roadmap to Diffuse Ergonomic Innovations in the Construction Industry: There Is Nothing So Practical as a Good Theory. *International Journal of Occupational and Environmental Health*, *13*(1), 46–55. https://doi.org/10.1179/107735207800245054

Woldstad, J. C., & Chaffin, D. B. (1994). Dynamic push and pull forces while using a manual material handling assist device. *IIE Transactions (Institute of Industrial Engineers)*, *26*(3). https://doi.org/10.1080/07408179408966610

Yazdani, A., & Wells, R. (2018). Barriers for implementation of successful change to prevent musculoskeletal disorders and how to systematically address them. *Applied Ergonomics*, *73*(April), 122–140. https://doi.org/10.1016/j.apergo.2018.05.004

Zare, M., Black, N., Sagot, J. C., Hunault, G., & Roquelaure, Y. (2020). Ergonomics interventions to reduce musculoskeletal risk factors in a truck manufacturing plant. *International Journal of Industrial Ergonomics*, *75*. https://doi.org/10.1016/j.ergon.2019.102896