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Review

Technologies for Reducing Musculoskeletal Disorders in Nursing Workers: A Scoping Review

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Abstract

Musculoskeletal disorders (MSDs) remain a critical occupational health issue for nursing personnel worldwide, resulting from physically demanding tasks such as patient handling and prolonged working hours. These injuries not only compromise nursing staff's health but also impair their performance, productivity, and overall well-being. This review analyzes the current state of assistive technologies aimed at preventing MSDs in nursing staff, highlighting their effectiveness, implementation challenges, and potential benefits. A systematic selection of the scientific literature from major databases including Web of Science, Scopus, ScienceDirect, PubMed, Taylor & Francis, and ProQuest was conducted, complemented by open-access patent records. The screening process, involving two independent reviewers, achieved moderate agreement (Cohen's Kappa = 0.418). The findings reveal that the most affected anatomical areas include the back, shoulders, and knees. Technological interventions are classified into three main categories: physical assistance devices, digital monitoring tools, and training programs. These integrated approaches offer promising avenues to enhance occupational safety, reduce injury rates, and improve nurses' quality of life and professional performance.

Keywords: musculoskeletal disorders; nursing workers; assistive devices; wearable devices; robotic systems

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1. Introduction

The rapid increase in the demand for nursing services in the People's Republic of China, coupled with the slow growth in the number of qualified nurses, has led to a considerable rise in nurses' workloads. Much of their work involves transferring patients and handling heavy medical equipment, which frequently results in low back pain [1].

This issue is not unique to China; according to the U.S. Bureau of Labor Statistics, nurses represented the largest workforce in the United States in 2022, and more than 1.1 million nursing positions needed to be filled to prevent staffing shortages. Moreover, the incidence of work-related musculoskeletal disorders (WMSDs) among nurses is higher than the average for other occupations [2].

MSDs significantly affect both individual nurses and healthcare organizations. At the individual level, nurses often experience chronic pain, muscle fatigue, circulatory problems, stress, and other physical and mental health issues [3–5], which can lead to reduced quality of life, physical limitations, early retirement, and emotional distress [6]. It is estimated that between 50% and 90% of nursing staff suffer from some form of MSD during their professional careers [7]. At the organizational level, these disorders diminish work quality and productivity, increasing absenteeism and negatively impacting patient care [7]. Figure 1 shows U.S. Bureau of Labor Statistics data of musculoskeletal disorders in nurses.

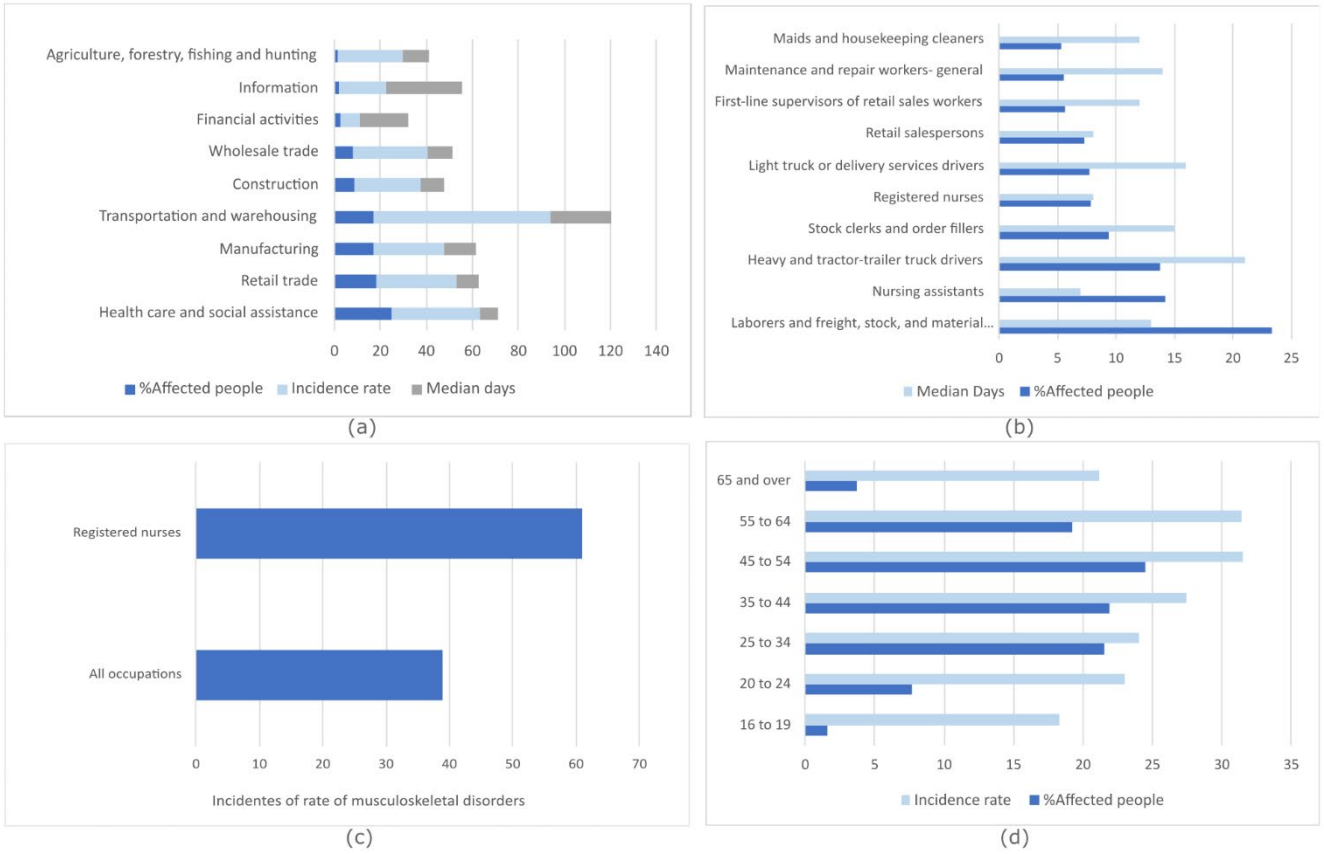


Figure 1. Statistics on musculoskeletal disorders; (**a**) % affected people, incidence rate, and median days away from work for injuries and illnesses involving musculoskeletal disorders by selected industries; (**b**) % affected people, and median days away from work for injuries and illnesses involving musculoskeletal disorders by selected occupations; (**c**) incidence rates of musculoskeletal disorders, all occupations vs. registered nurses; (**d**) affected people and incidence rate of injuries and illnesses involving musculoskeletal disorders by selected age groups.

A 2019 study conducted in the United Kingdom reported 60,000 cases of work-related musculoskeletal disorders among health and social care workers, a number significantly higher than that reported in other industries [8]. Data from the U.S. Bureau of Labor Statistics (2011–2018) corroborate these findings: healthcare and social assistance workers exhibit the highest incidence rates of MSDs, with nurses accounting for 60% of all reported cases. Nursing assistants rank second among the most affected professions, and the majority of cases occur in individuals aged 25–64, particularly those aged 45–64 [9].

WMSDs in nursing staff are largely associated with tasks requiring both static and dynamic musculoskeletal activity. Static work involves sustained muscle contraction in a fixed position, while dynamic work alternates between contraction and relaxation [10]. Addressing this issue is essential, as nurses are a cornerstone of healthcare systems and play a crucial role in achieving the Sustainable Development Goals (SDGs) [6]. Ensuring their physical and mental well-being strengthens health systems, improves patient outcomes, and contributes to building a healthier and more sustainable world.

Figure 2 illustrates the relationship between the well-being of nursing personnel and the implementation of the United Nations (UN)'s sustainable development goals.

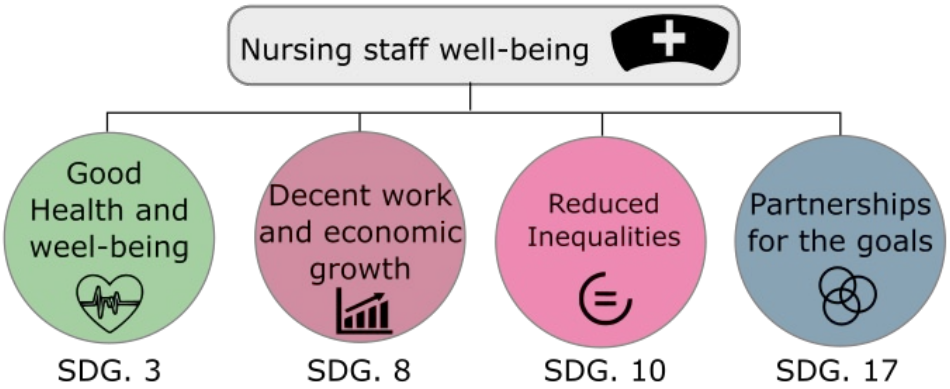


Figure 2. The well-being of nurses and their contribution to the UN Sustainable Development Goals: 3, 8, 10, and 17.

Protecting and promoting the health and well-being of nurses is critical to strengthening health systems. Ensuring safe working conditions, preventing occupational diseases, and fostering healthy environments not only improves their quality of life but also has a direct impact on the quality of care provided to the population (SDG 3) [10].

Promoting the well-being of nurses requires the provision of safe, healthy, and equitable working conditions, in line with the principles of decent work. These conditions not only ensure respect for labor rights, but also foster the stability, motivation, and professional development of health workers (SDG 8).

The well-being of nurses is key to promoting fair and equitable working conditions. When a decent work environment is guaranteed, with equal opportunities and treatment, it contributes to reducing inequalities within the health sector. This not only improves the quality of life of workers but also strengthens equity in health services (SDG 10).

Ensuring the well-being of nurses requires the joint commitment of governments, healthcare institutions, international organizations, and society as a whole. Building strong and coordinated partnerships enables the pooling of resources, knowledge, and efforts to improve working conditions and strengthen health systems (SDG 17) [11].

Several risk factors contribute to the development of musculoskeletal disorders in nursing workers. These include handling physical loads exceeding 10 kg, working hours exceeding 8 h, insufficient staff, inadequate posture, and the lack of preventive measures to avoid these disorders [12,13]. In addition, psychological factors such as anxiety and depression are also linked to the onset of these disorders [14].

Several factors have been identified that may facilitate or hinder the implementation of preventive practices for MSDs. These factors are organized into stages from the acquisition of knowledge to the application of these practices [15], as shown in Figure 3.

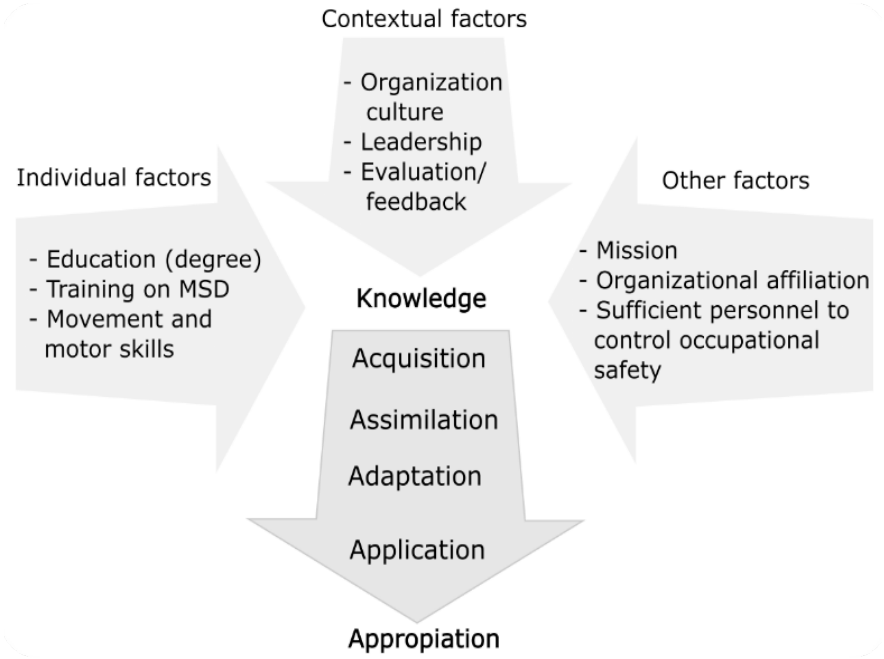


Figure 3. Risks factors types studied in the application of WMSD prevention practices.

According to the PARiHS (Promoting Action on Research Implementation in Health Services) model [16], these factors encompass contextual, individual, and other aspects, which vary by region, educational level, and political context. Knowledge of best practices is essential for their assimilation and successful application. Four risk factors contribute to the development of musculoskeletal disorders in the nursing setting, which affect the well-being of staff. These factors are as follows: (1) demographic and occupational characteristics, (2) the physical conditions of the environment, (3) psychosocial aspects, (4) the organization of the workplace. Together, these elements can impact both the physical and mental well-being of workers, as well as their performance and professional satisfaction (Figure 4) [17].

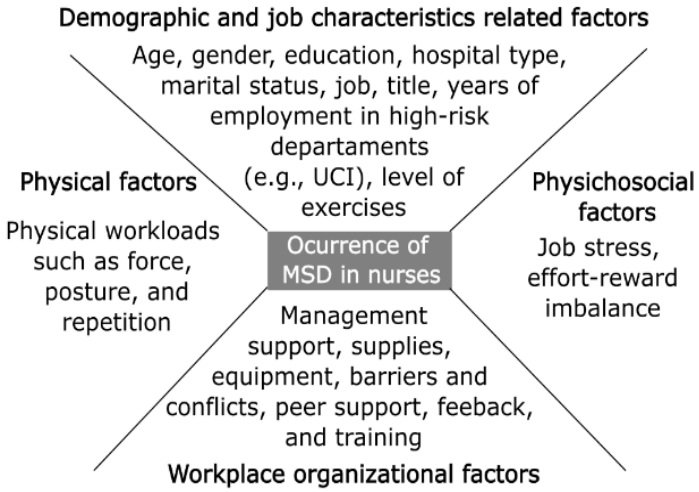


Figure 4. Risk factors for the occurrence of MSD in nurses.

The factors presented in Figure 4 exert a multifaceted impact, encompassing aspects such as the type of hospital, the work environment, and the level of physical activity among workers. Several of these factors are often underestimated by healthcare professionals; therefore, more in-depth studies are required to adequately establish their relationship with the development of MSDs among nursing staff.

During the COVID-19 pandemic, a significant increase in the incidence of WMSDs was observed among nurses, particularly in the lower back (72%), knees (64%), and neck (60%), in addition to an increase in wrist and palm disorders [18]. Despite the implementation of ergonomics programs and the promotion of healthy lifestyles [19], WMSDs continue to represent a considerable problem for this professional group. Further research is needed to reduce their prevalence, promote health, and improve staff productivity [18].

The findings presented in this manuscript are structured into three distinct stages: prediction, detection, and intervention. In the prediction stage, high-risk scenarios are identified through objective metrics, including task frequency, patient-handling loads exceeding 10 kg, and prolonged work shifts. This phase also incorporates the documented prevalence of musculoskeletal symptoms. The detection stage entails continuous monitoring of posture and workload using portable inertial measurement units, surface electromyography, or validated assessment instruments such as the Nordic Musculoskeletal Questionnaire. Key indicators in this stage include trunk flexion angles, cumulative exposure durations, and deviations in the center of gravity beyond predefined thresholds. Finally, the intervention stage consists of the deployment of assistive technologies or ergonomic programs once the thresholds established in the preceding stages are surpassed, with quantifiable outcomes such as reductions of at least 30% in physical load, electromyographic activity, or postural deviations.

The review presented in this manuscript is particularly relevant as it highlights the impact of assistive technologies in the prevention of MSDs among nursing staff, a group particularly vulnerable due to the high physical demands of their work. Through the analysis of solutions such as lifting devices, automated beds, smart sensors, and exoskeletons, the study demonstrates how these tools can improve ergonomic conditions, reduce the risk of injury, and promote safer and more sustainable work environments. Moreover, it provides valuable evidence for informed decision-making in healthcare institutions and for the development of policies aimed at enhancing staff well-being and improving the quality of patient care.

2. Methodology

The systematic review presented was conducted by establishing a review protocol in accordance with the guidelines of the PRISMA® methodology. The dataset with the details of the revision carried out can be consulted at [20]. Scientific documents published in the last fifteen years, belonging to scientific databases such as Scopus, ScienceDirect, PubMed, Web of Science, and Taylor & Francis, have been included in the reference information.

The Reporting Items for Systematic Reviews and Meta-Analysis (Table A1 in Appendix A) has been used, in which the number of pages containing relevant information has been specified in the relevant sections of the document.

The development of this review was carried out in three stages, which involved formulating the research questions, delimiting the scope, and conducting an exhaustive search to extract relevant information from the selected publications.

The primary objective of this research was to identify technologies aimed at reducing musculoskeletal risks in nurses, as documented in the scientific literature and patent databases. The second objective was to classify and categorize these solutions. The third objective was to examine the impact of these technologies on productivity and quality of life, and, finally, to explore their future prospects for implementation.

The research questions posed for extracting information from the selected scientific articles were as follows. RQ1: What are the tasks associated with the generation of musculoskeletal disorders in nurses? RQ2: What technologies have been developed to reduce the risk of musculoskeletal disorders for nurses? RQ3: What are the impacts on the use of

these technologies? RQ4: What are the limitations and challenges in the implementation of technologies to reduce the risk of musculoskeletal disorders?

Following the identification of the included studies, data extraction was performed in accordance with the predefined research questions to ensure consistency and reproducibility. Subsequently, the relevance and methodological contributions of each study were critically appraised using a set of quality assessment criteria. These criteria, designed to evaluate aspects such as study design, methodological rigor, and relevance to the research objectives, are outlined in detail in Table 1.

Table 1. Quality assessment questions for papers.

Quality Assessment Questions	Answer
Does the article describe the tasks that cause musculoskeletal disorders in nursing workers?	(+1) Yes/(+0) No
Does the paper describe the frequency of musculoskeletal disorders affecting nursing workers?	(+1) Yes/(+0) No
Does the document present or propose solutions to reduce the risk of musculoskeletal disorders in nursing workers?	(+1) Yes/(+0) No
Is the journal or conference in which the paper was published indexed in SJR?	(+1) if it is ranked Q1, (+0.75) if it is ranked Q2, (+0.50) if it is ranked Q3, (+0.25) if it is ranked Q4, (+0.0) if it is not ranked

Figure 5 presents the workflow for selecting reference articles obtained from the search carried out using the following keywords: technologies for reducing musculoskeletal disorders or injuries in nursing workers. Articles from the last fifteen years were considered, including journals, articles, and conference papers. Additionally, for the introductory part, figures provided on the official website of the U.S. Bureau of Labor Statistics were used.

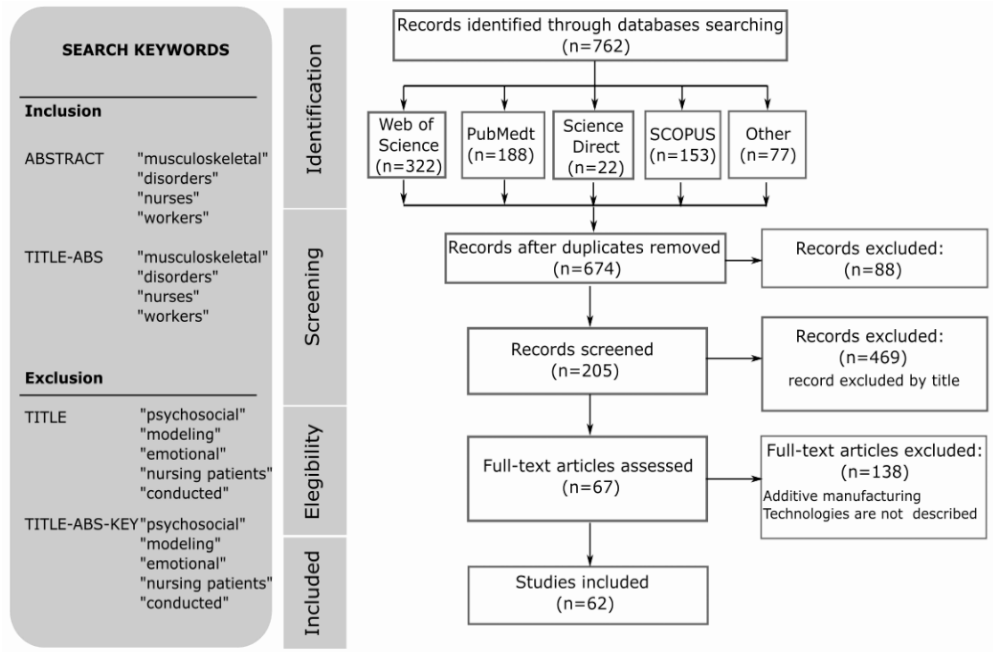


Figure 5. Workflow in the selection of information documentation.

2.1. Inclusion Criteria

Scientific articles and patent documents were selected using a search string designed to cover studies on technologies applied to prevent or reduce musculoskeletal disorders in nursing staff. The string used was as follows: (“musculoskeletal disorder” OR “MSD”

OR “musculoskeletal injury” OR “musculoskeletal pain”) AND (“nursing” OR “nurse” OR “healthcare” OR “patient care”) AND (“technology” OR “device” OR “equipment” OR “tool”) AND (“ergonomics” OR “posture” OR “lifting” OR “support”) AND (“prevention” OR “reduction” OR “management” OR “intervention”). This made it possible to identify relevant documents published over the last ten years that addressed the design, development, or evaluation of devices, tools, or technological solutions aimed at improving ergonomic conditions and reducing the physical effort of nursing staff in their work activities.

2.2. Exclusion Criteria

Documents that, despite partially coinciding with the terms of the search string, did not present a direct relationship with nursing staff or did not include a specific technological proposal focused on the prevention or management of musculoskeletal disorders were excluded. Likewise, studies focused exclusively on other occupational groups or technologies not applied to the health context were discarded. Publications without scientific support, duplicate documents, and those technological proposals without preliminary validation or specific application in clinical or patient care settings were also excluded.

3. Results

The results of this review have been organized into four key sections: the first describes common tasks that frequently cause muscular problems in nursing staff; the second analyzes technological advances to prevent these disorders; the third addresses the challenges and limitations in implementing these solutions; and the fourth section highlights the prospects for the future use of these technologies. The second section, which addresses technologies that contribute to reducing musculoskeletal disorders among nursing workers, has been organized according to the findings, as specified in Figure 6.

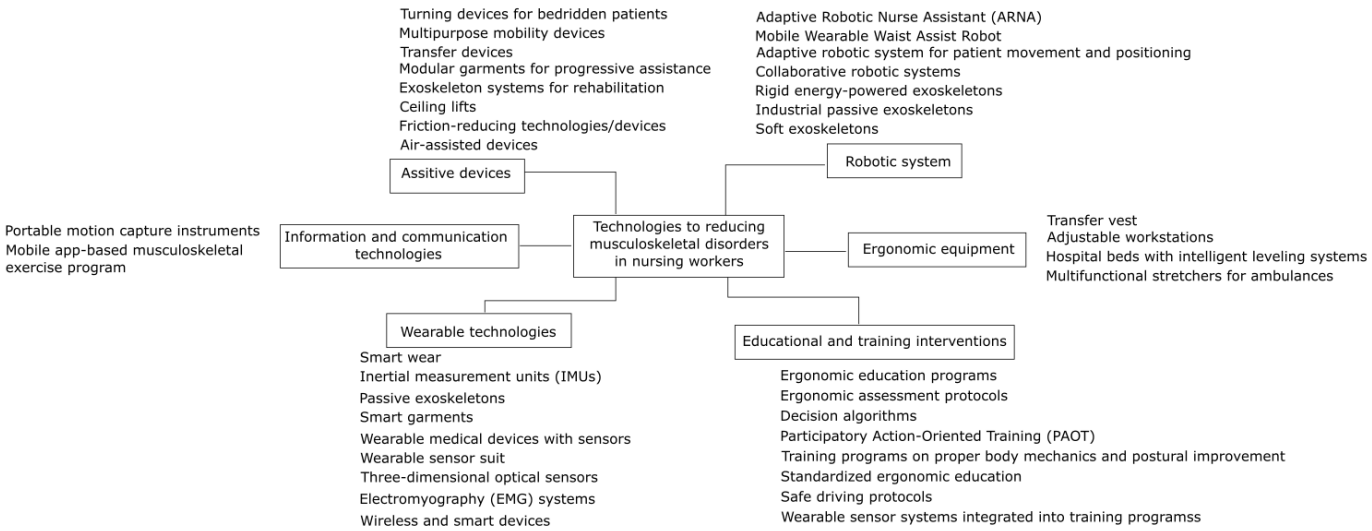


Figure 6. Technologies that contribute to reducing musculoskeletal disorders among nursing workers.

3.1. Tasks That Involve Risk of Musculoskeletal Disorders

Nurses perform a variety of tasks that involve both physical and mental demands. Some tasks require a great deal of physical effort, repetitive movements, and awkward postures. On the mental side, certain circumstances at work can generate pressure, such as extended and intensive shifts resulting from personnel shortages. Both physical and mental activities have effects on the occurrence of musculoskeletal disorders [21].

Tasks related to maintaining hygiene in various areas of patient care, such as changing the position of patients in bed, transferring patients, home support, and administering medications, require prolonged postures and the handling of patients and heavy equipment, as well as considerable efforts by nursing staff [21–23].

Repetitive and routine tasks such as writing, typing, and handling instruments or carts used to transport medical supplies [8] can increase the risk of musculoskeletal disorders, particularly those associated with physical fatigue. In addition to this, nursing work is often performed in long working hours with overtime, which also requires the use of complex medical devices and sudden changes in activities [6]. Table 2 presents the tasks performed by nurses and the associated risks, categorized by the activities performed by nursing staff.

Table 2. Tasks performed by nurses and associated risks.

Nursing Tasks/Activities	Risk Factors	Refs.
Maintenance of hygiene in the work area	Static and dynamic work of the musculoskeletal system	[4]
Patient transfer	Handling physical loads, improper postures	[22,24]
Medication management	Repetitive motions, use of upper extremities	[8]
Home support	Extended working hours, lack of rest	[5,18]
Medical records documentation	Repetitive motions, extended use of data visualization screens	[25]
Patient Lifting and mobilization	Manual lifting of loads, awkward postures	[26]
Sudden change in posture activities	Awkward postures, restricted spaces for patient restraint and handling, inadequate work organization	[27–29]
Performing invasive procedures	Awkward postures, inadequate workspace organization	[29,30]
Work in long shifts	Extended work shifts, work overload	[31,32]
Carrying out urgent activities of high demand and psychological pressure	Extended work hours, time pressure, insufficient rest time, high responsibility	[27]
Large number of tasks during extended working hours	Extended work hours, work overload	[33,34]
Management of technological equipment and computer equipment.	Repetitive motions, extensive use of data visualization screens	[35,36]

The activities of the nursing worker are frequently carried out with static postures, such as standing or sitting, for long periods, as is the case with invasive interventions or procedures [13]. Lack of rest time has been linked to an increased risk of developing musculoskeletal disorders [23].

Tasks such as the manipulation of mechanical equipment that are activated by the manual force of nurses can increase the risk of developing musculoskeletal disorders if adequate training in ergonomics and an adequate procedure for the use of this equipment have not been provided; a similar situation occurs with the techniques of lifting or moving patients [35].

Among the various tasks that increase the risk of WMSDs among nursing personnel, lifting, transferring, and mobilizing care-dependent patients have been identified as the primary contributing factors [10]. These activities are frequently associated with improper postures [5], the use of inadequate equipment, insufficient preventive training, and low levels of physical activity [37].

In addition, inadequate work surfaces and inappropriate footwear influence safety by increasing the risk of falls and slips [7]. Individual factors, such as age, height, physical

condition, and a history of musculoskeletal diseases, also play a role in the occurrence of WMSDs if they are not adequately considered [35].

The activities carried out by nursing staff, combined with the poor control of risk factors, can affect their health and well-being when MSDs develop, generating pain, paresthesia, and muscle fatigue, which in turn deteriorates their quality of life [7]. These disorders occur in various areas of the body, being especially significant in the upper extremities, where conditions such as carpal tunnel syndrome, tendonitis, and epicondylitis are identified [17,28]. Prolonged work in front of a computer can cause neck injury [32], which requires more effective preventive management [7].

In the back area, pain and injuries are common, although there are still no clearly effective preventive methods [38]. During the COVID-19 pandemic, a high prevalence of WMSDs was reported in the upper back (61.4%), and neck (73.4%) [39], with lumbar symptoms being the most common (90.4%) among those who had direct contact with patients, in addition to tendonitis, bursitis, carpal tunnel syndrome, and herniated discs [40]. Professionals who cared for patients with COVID-19 had more wrist, palm, ankle, and knee disorders than those who did not [39].

The most common symptoms include lower back, shoulder, and neck pain [37], as well as chronic muscle pain, fatigue, circulatory problems, headaches [36], and spinal injuries [41]. Ankle and foot conditions, such as sprains and tears [42,43], are also reported, with the lower back, knees, and neck being the most affected areas [35]. These injuries account for 34% of lost workdays in the U.S. and one-third of workers' compensation spending, making them the leading cause of functional rehabilitation in nursing.

Prevalence rates of WMSDs in nursing vary between 54% and 92%, with symptoms of low back pain standing out as one of the most common, with a prevalence of over 87% and an annual incidence of 47%. Pain in the shoulder region is also frequently reported, affecting more than 40% of staff [2]. Despite multiple studies, WMSDs continue to be a major challenge in the health workplace, especially for nursing personnel, so it is necessary to continue developing prevention and management strategies from a multidisciplinary approach [44]. Figure 7 shows percentages of studies on WMSDs in different parts of the body, as well as prevalence values reported in previous evaluations [35,45].

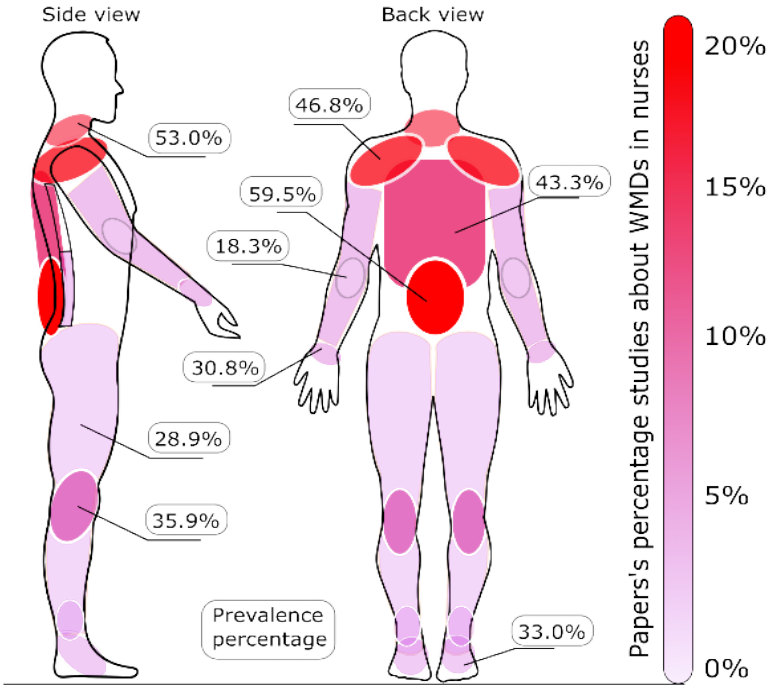


Figure 7. WMDs and prevalence percentages about body parts in the human body.

Finally, psychosocial aspects such as stress and work pressure are linked to these disorders [3], while a good social climate can increase staff tolerance to demanding situations, making it necessary to monitor mental health.

3.2. Technologies That Contribute to Reducing Musculoskeletal Disorders in Nursing Workers

Several studies have reported the development of various technological solutions aimed at mitigating WMSDs. These include ergonomically designed equipment (e.g., adjustable hospital beds, height-adaptable workstations), assistive devices (e.g., patient transfer aids, lifting devices), robotic systems (e.g., robotic arms for patient handling), educational and training interventions (e.g., simulation-based ergonomic training programs), wearable technologies (e.g., posture-monitoring sensors, exoskeletons), and information and communication technologies (e.g., mobile applications for workload monitoring and ergonomic reminders). This section describes emerging alternative solutions currently under development that could contribute to reducing the prevalence of WMSDs among nursing staff.

3.2.1. Equipment to Improve Ergonomics

The growing concern for the occupational health and safety of workers in the health sector has led to the development of various technological solutions aimed at reducing nurses' physical effort and improving the safety of both staff and patients [46]. These advancements include transfer vests, adjustable workstations, hospital beds with intelligent systems, and multifunctional stretchers for ambulances, each with an innovative approach to ergonomics and functionality [47].

Transfer vests designed for healthcare personnel have been created to provide ergonomic support during patient lifting or repositioning maneuvers. A prominent example is the vest described in patent US10420689B1 (Figure 8a), which features an adjustable one-piece design to provide efficient assistance during manual transfers. This vest evenly distributes pressure on the patient's body, reducing the risk of skin injuries such as tears or bruises, and decreasing the likelihood of joint dislocations during lifting maneuvers. In addition, its design promotes a proper posture of the nurses, reducing the risk of injuries to the shoulders, wrists, and back of the professional.

Another relevant patent is US9015880B1 (Figure 8b), which describes a manual transfer vest that helps to reduce fatigue, pain, and loss of strength in nurses, promoting safety during patient lifting. This vest features several grip points, strategically placed for easy patient handling, and is made of soft, lightweight materials, making it both comfortable and durable during repeated use.

On the other hand, EA031279B1 (Figure 8c) presents a self-activated booster vest with sensory feedback, a significant advancement that promotes the nurse's proper posture through sensory stimuli. This vest combines a load transfer element with a feedback system that corrects the wearer's posture during lifting maneuvers, helping to minimize the risk of occupational injuries to nurses.

Adjustable workstations are another key solution in the ergonomic design of clinical environments. Recent research suggests that the use of adjustable workstations, especially those mounted on the wall and with mobile computers, can significantly reduce ergonomic stressors in the workplace [46]. These stations enable workers to adjust their work environment to their physical needs, thereby minimizing muscle tension and improving posture during nurses' daily tasks [47] (Figure 8d).

In addition, hospital beds with intelligent leveling systems, such as those described in patent CA2472491C (Figure 8e), are designed to maintain a level position while adjusting their height. This system utilizes electric linear actuators with internal position sensors to

adjust the bed height efficiently, ensuring smooth movement without noticeable tilts and reducing the risk of injury to both patients and staff during adjustments.

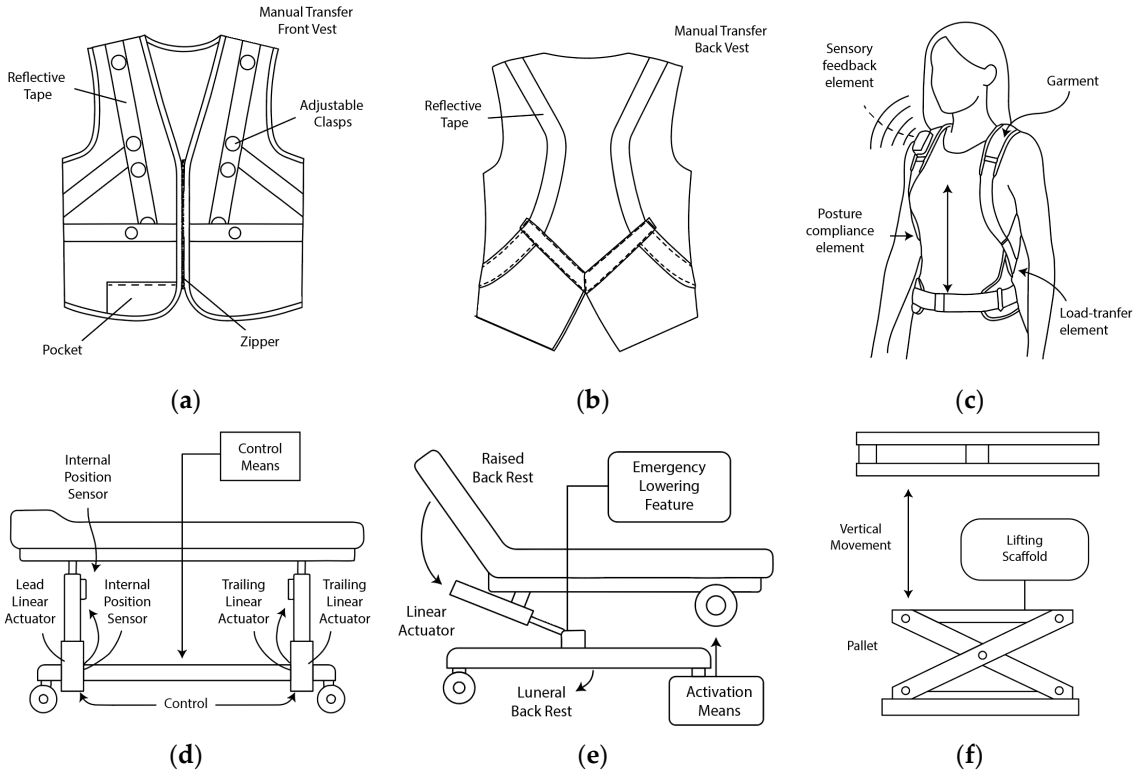


Figure 8. (**a**) Adjustable manual transfer vest. (**b**) Manual transfer vest. (**c**) Self-activated booster vest with sensory feedback. (**d**) Adjustable workstations. (**e**) Height-adjustable patient bed leveling system. (**f**) Ambulance stretchers for patient transport.

In the field of patient transport, multifunctional stretchers represent a significant advance. Patent EP0773773B1 (Figure 8f) describes an ambulance stretcher that allows both lying and sitting transport, adapting to different environments and rescue conditions. This stretcher, featuring a rigid support frame and articulated sections, can be easily transformed into a transport chair, making it convenient to use in emergencies [48]. Additionally, its structure incorporates large-diameter wheels and non-conductive materials, such as fiberglass, which enhances safety in electrical environments.

Technological innovations in ergonomic for equipment, such as transfer vests, adjustable workstations, hospital beds with intelligent leveling systems, and multifunctional stretchers, are revolutionizing the way clinical tasks are performed. These advances not only improve patient safety and comfort but also significantly reduce the risk of injury to nurses, promoting better occupational health. The multidisciplinary effort behind these solutions, which integrates functionality, ergonomics, and technology, reflects an ongoing commitment to improving the work environment and quality of patient care.

3.2.2. Assistive Devices

The advancement of assistive devices in clinical settings represents a necessary response to the high rates of MSDs that affect nursing staff, due to the physical demands inherent in patient care. These technologies have been developed to facilitate critical tasks, such as patient transfer, repositioning, and rehabilitation, and promote safer, more efficient, and ergonomic working conditions. The integration of these devices not only enhances the quality of patient care but also significantly reduces the physical burden and risk of injury to healthcare workers [6].

Among the most outstanding solutions are turning devices for bedridden patients, such as the one proposed in patent US20190175428A1, which features a semicircular structure that allows immobilized patients to be repositioned without requiring excessive force from the nurses. This designs, which incorporates adjustable levers and harnesses (Figure 9a), is designed to ensure patient safety during movements and facilitate maneuvers that traditionally pose a high risk to staff [6]. Additionally, the multipurpose mobility device described in WO2009076698A1 features a traction mechanism (manual or motorized) connected by straps to a base positioned under the patient. This system enables the patient to change position in a controlled and gentle manner (Figure 9b), with clinical applications such as daily hygiene or the prevention of pressure ulcers, thereby improving both the efficiency of the process and the patient's dignity [8].

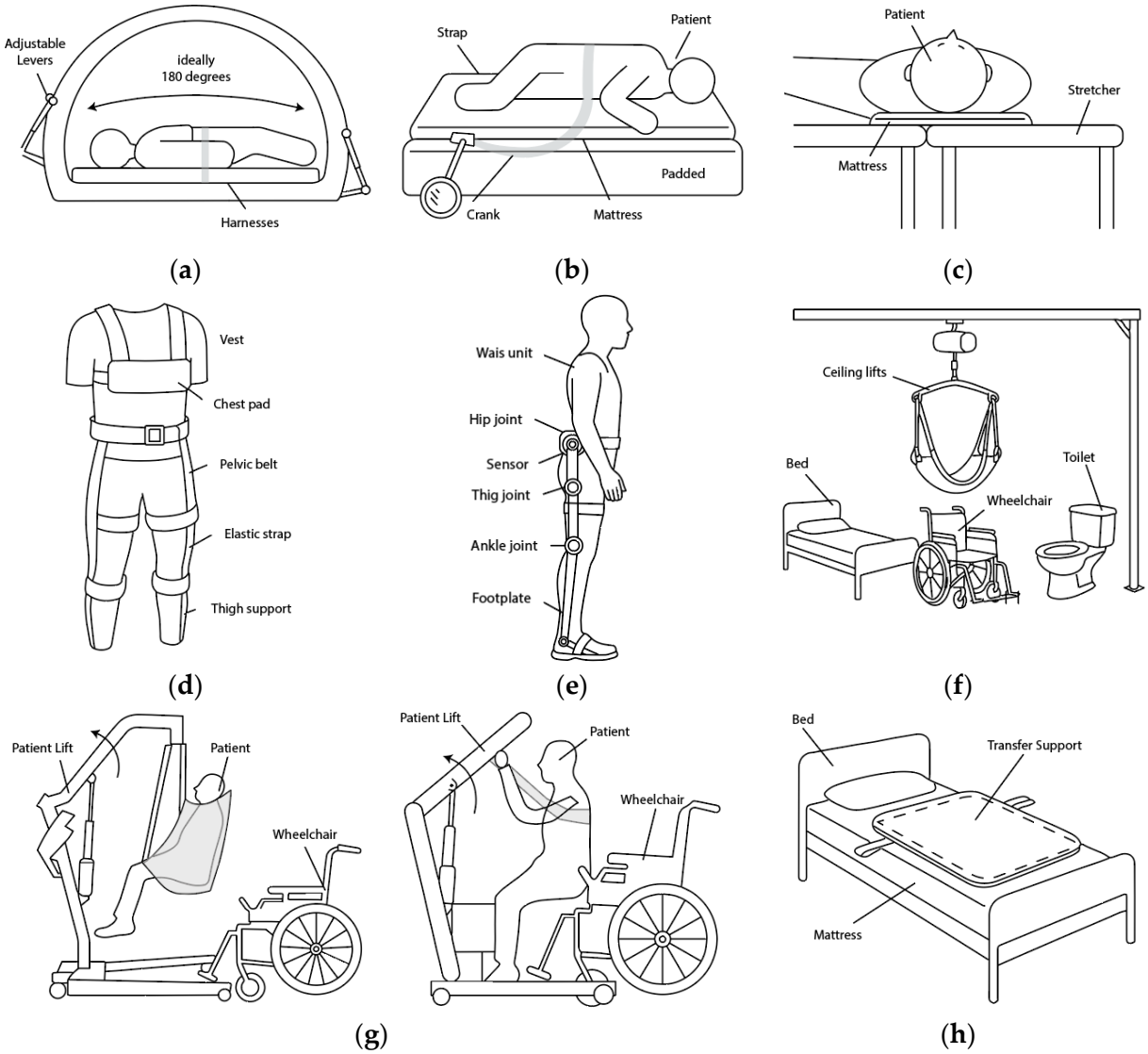


Figure 9. Assistive devices: (**a**) Turning devices for bedridden patients. (**b**) Multipurpose mobility device. (**c**) Transfer device. (**d**) Modular garments of progressive assistance. (**e**) Exoskeletons for rehabilitation. (**f**) Friction reducing technologies. (**g**) devices for mobilization and repositioning. (**h**) Tranfer device.

The RU2414876C1 transfer device (Figure 9c,h) is aimed at the horizontal transfer of patients between surfaces (such as from the bed to the stretcher). It features a cover with sliding material and a hygienic design that reduces friction, enhancing the device's

ergonomics and facilitating washing and reuse. This type of solution promotes the sustainability of hospital equipment and safety in the healthcare environment [9].

Likewise, modular garments have been developed for progressive assistance, such as the one described in document US9420832B2 (Figure 9d), which enables the patient to be assisted in multiple tasks (walking, turning, sitting, or standing up) through a configurable system of belts, vests, and adjustable straps. This technology is particularly useful in rehabilitation processes, as it enables personalized care to be tailored to the patient's progress and the therapist's needs, thereby reducing the risk of injury to both the patient and the clinical staff [12].

A further step in this line is exoskeleton systems for rehabilitation, such as the one presented in CN108186294B (Figure 9e), which integrates multiple motorized units in the waist, hips, thighs, and legs, with intelligent sensors that recognize the phases of gait. These systems provide personalized and adaptable assistance in real-time, enabling patients to regain functional mobility with increased stability, comfort, and efficiency. Additionally, they are made of lightweight materials, such as carbon fiber, and include quick-release mechanisms for emergencies [14].

Ceiling lifts (Figure 9f) and friction-reducing technologies (Figure 9g) have been shown to be highly effective in preventing musculoskeletal injuries among nursing staff by significantly reducing physical exertion during patient mobilization and repositioning. Studies report that these aerial systems reduce the incidence of MSDs by 59.8%, lost working days by 90%, and compensation claims by 95%, in addition to reducing the required manual force by up to 70% [49].

In particular, friction-reducing devices enable the patient to slide onto the bed, minimizing contact and effort, thereby reducing the risk of injury during repetitive tasks [49].

From a global perspective, the use of electromechanical devices and transfer systems has been shown to significantly reduce the prevalence of MSDs among nurses. Recent studies have reported reductions of up to 59.8% in injury incidence, 90% in lost workdays, and 95% in compensation claims [50]. These positive effects are partly because these devices reduce the manual force required during patient lifting and positioning, as evidenced by air-assisted devices (Figure 10) and friction-reducing devices, which decrease physical effort by up to 70% [51].

In terms of ergonomic impact, motorized devices have shown the most significant reductions in the risk of MSDs, with a standardized mean difference of −3.32, according to recent reports [52]. These findings underscore the importance of continuing to promote the systematic use of assistive technologies in hospital routines.

However, the successful implementation of these devices does not depend only on their design or functionality, but also on the training of personnel, the ergonomic adaptation of the environment and the organizational safety culture. Health institutions must accompany technological adoption with training programs, biomechanical risk analysis, and occupational prevention policies.

Figure 10 presents a graph illustrating the relative frequency of terms associated with assistive devices aimed at reducing musculoskeletal disorders among nurses. The analysis included studies on technologies, equipment, and support tools, focusing on the keywords workstation, transport, transference, booster, and bed. The results show a higher occurrence of transfer devices and adjustable beds, which are frequently associated with the reduction in musculoskeletal disorders in nursing staff.

Figure 10 shows a greater frequency of the use of the word transfer in studies related to the topic addressed, followed by lifts and transport systems, with very few workplaces and boosters being addressed.

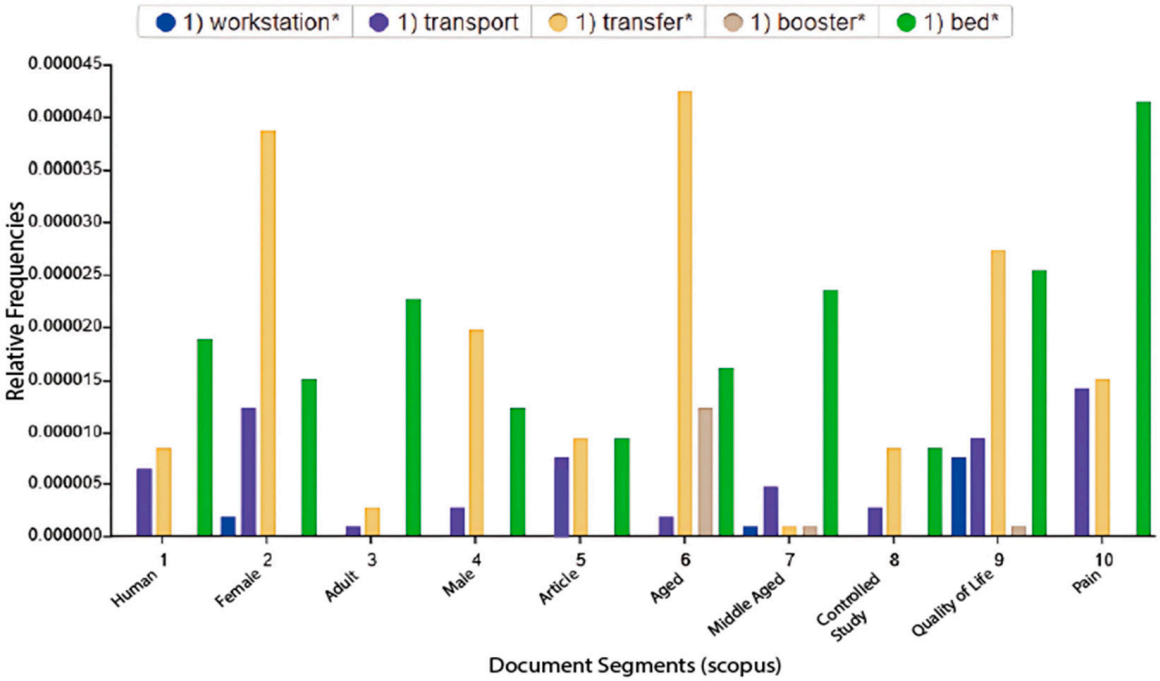


Figure 10. Relative frequency of terms associated with assistive devices to reduce musculoskeletal disorders in nurses. * It is used to perform a targeted search.

3.2.3. Robotic Systems

The development of robotic systems in the hospital environment has become increasingly important as a response to the shortage of healthcare personnel and the high incidence of MSDs affecting nursing staff. These technological solutions, designed to assist with physical and cognitive tasks, are transforming clinical routines and improving both patient safety and the ergonomics of the work environment.

One of the most representative systems is the Adaptive Robotic Nurse Assistant (ARNA), a collaborative robot designed to assist nursing staff (Figure 11a) in both physical tasks (such as walking with the patient or handing over objects) and non-physical tasks (such as observation and feedback). Evaluated in a simulated hospital environment using the Technology Acceptance Model, ARNA demonstrated high acceptability among nursing students, exceeding the average in internal consistency of the questionnaires applied. Its potential for integration into clinical settings is promising, although opportunities for improvement have been identified in terms of flexibility, ease of operation, and autonomy [2].

A particularly innovative development is the mobile wearable waist assist robot (Figure 11b), a wearable exoskeleton that uses pneumatic artificial muscles as power actuators. The user wears it like a backpack, providing direct assistance with lifting or prolonged static holding tasks, thereby reducing lower back pain. In controlled tests, the device was able to reduce the electromyographic activity of the erector spinae muscle by 39% and 27% ($p < 0.05$), in addition to decreasing angular velocity and deviation from the center of gravity during load handling, confirming its effectiveness in preventing MSDs [1].

In the same vein, patent US12090629B2 presents an adaptive robotic system focused on the movement and safe positioning of patients with reduced mobility (Figure 11c). The design features a support base with a sliding surface and fasteners, enabling patients to be efficiently transferred between surfaces, such as from bed to stretcher, with minimal physical demands on healthcare staff. This invention contributes to improving the ergonomics of clinical work, reducing the risk of injury, and increasing patient safety.

Collaborative robotic systems, in general, stand out for their ability to reduce physical effort in manual patient management tasks (Figure 11d). These devices have been shown

to be effective in patient replacement and manipulation, helping to reduce the risk of injury among nurses and confirming the feasibility of robotic repositioning [51,53].

The incorporation of nanoelectronics and new materials has enabled the development of more compact and versatile systems, applicable in both invasive and non-invasive procedures, which has facilitated nurses' work in conditions of prolonged effort [54]. In this context, exoskeletons adapted to nursing staff have been classified into three broad categories: rigid energy-powered exoskeletons, industrial passive exoskeletons, and soft exoskeletons [55,56]. Each offers different levels of support and adaptability, opening up new possibilities for injury prevention and improved clinical performance.

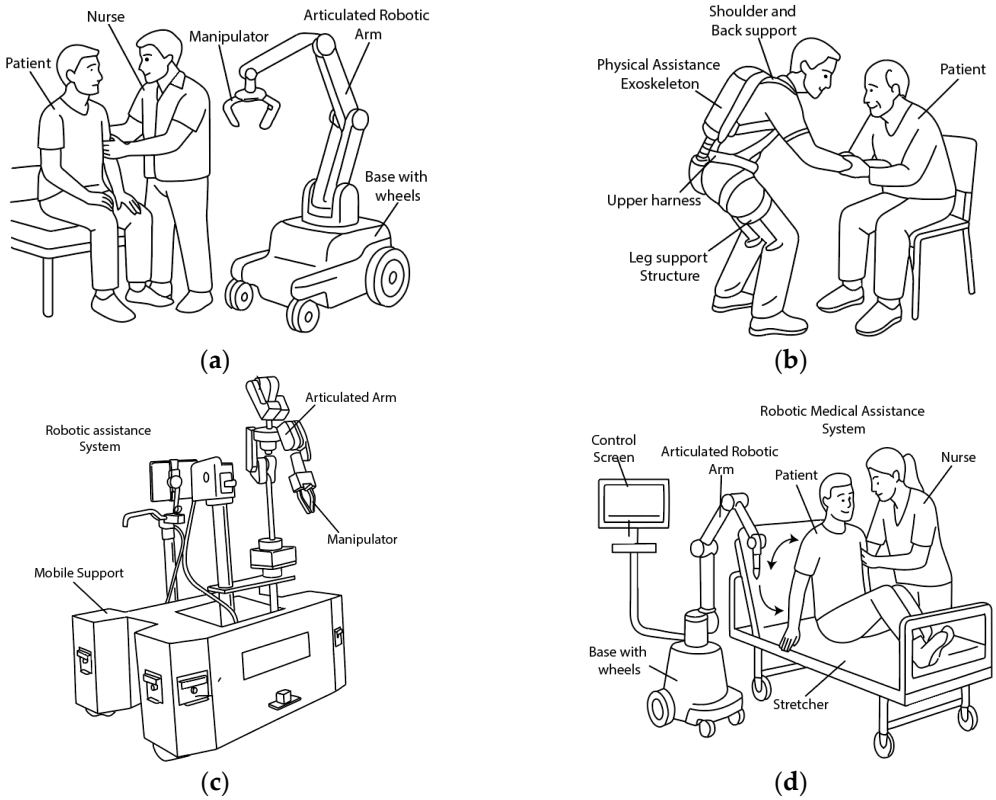


Figure 11. Robotic systems: (**a**) Adaptive robotic nurse assistant. (**b**) Mobile wearable waist assist robot. (**c**) adaptive robotic system. (**d**) Collaborative robotic systems.

Together, robotic care systems for nurses represent a significant advancement in transforming the hospital environment towards safer, more efficient, and sustainable models. Training processes and ergonomic validation must accompany its adoption to ensure its effective integration into daily clinical practice.

3.2.4. Educational and Training Interventions

The implementation of ergonomics education programs is a fundamental strategy to reduce MSDs among nursing staff. Evidence shows that training in ergonomic techniques and the proper use of assistive devices, complemented by ergonomic assessment protocols and decision algorithms, is effective in preventing occupational injuries [53,57]. Comprehensive programs that combine training with the implementation of assistive equipment have shown significant reductions in patient handling injuries, missed workdays, and costs associated with workers' compensation [56], highlighting the importance of multifaceted approaches that include periodic evaluations, ongoing training, and the availability of devices.

Participatory approaches have emerged as particularly effective methodologies. Participatory Action-Oriented Training (PAOT), for example, has demonstrated success in identifying and implementing practical and cost-effective solutions to reduce ergonomic risk factors [58]. This model not only enhances adherence to preventive measures but also facilitates the contextualized adaptation of interventions, thereby increasing their long-term sustainability.

In terms of manual patient management, training programs that focus on proper body mechanics, improve postural, and the systematic use of lifting devices have proven effective in preventing low back pain among nurses [59]. These programs, when complemented with standardized ergonomic education and safe driving protocols [58], not only reduce the incidence of injuries but also promote a culture of occupational safety. The combination of these elements (specialized education, active staff participation, and the availability of resources) represents the most comprehensive strategy for addressing this occupational health problem.

Wearable sensor systems can be integrated into training programs to improve nurses' ergonomic practices, reducing physical stress during patient handling tasks [60,61]. These wearable technologies enable accurate measurements of exposure to hazardous activities, helping to identify high-risk activities and guiding ergonomic interventions [10–14].

3.2.5. Wearable Technologies

Wearable technologies have been developed for monitoring and correcting posture. Developments include smart wear, inertial measurement units, and passive exoskeletons.

Smart garments incorporate electronic devices and work in conjunction with smartphone apps to provide feedback and training, helping to maintain correct posture. They are designed to help nurses avoid awkward postures that can lead to MSDs [62,63].

Inertial measurement units (IMUs) are devices in certain areas of the nurse's body to monitor trunk flexion and other movements, providing real-time information to help maintain better posture during their activities, which reduces the risk of lumbar disorders [8,11].

Passive exoskeletons have been designed to support the shoulders and back, transferring the forces exerted when transferring patients to the floor, significantly reducing the physical load on nurses and thus mitigating the risk of MSDs [9,13]. The use of exoskeletons enhances the efficiency and productivity of nursing staff, enabling them to perform tasks with reduced effort and physical fatigue. Most exoskeletons have been designed with a focus on women's body shapes, featuring adjustable levels of arm assistance through the use of actuators. These developments are compact, intuitive to use, and employ lightweight materials such as carbon fiber and hexagonal aluminum structures [64]. Figure 12 shows some schematics of exoskeletons designed exclusively for nursing staff. The devices are designed to provide assistance and torque in the lower back, reducing the effort required by the worker.

The devices presented in Figure 12 work with multiple technologies, and their main objective is to reduce the physical load on the lower back, especially when assisting in the change in position and transfer of patients. The exoskeleton depicted in Figure 9a helps the nurse to regain their upright position by utilizing two flexible bars secured in the worker's arms. Figure 12b depicts a rigid exoskeleton utilizing a spring system to recover the wearer's position. The device presented in Figure 12c is a passive exoskeleton that utilizes elastic elements to maintain the nurse's upright position. The design presented in 12d features an exoskeleton with two handles on which the patient can hold on for support while the worker lifts it. Figure 12e has a backpack-like mechanism on the nurse's back to facilitate the lifting of heavy patients.

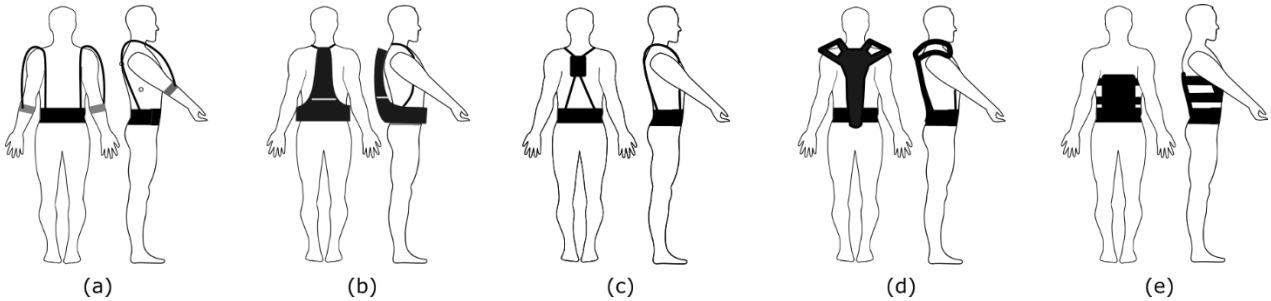


Figure 12. Passive exoskeletons for lumbar support of nursing workers: (**a**) Exoskeleton with flexible bars. (**b**) Exoskeleton with movement recovery springs. (**c**) Passive exoskeleton with elastic elements. (**d**) Exoskeletons with patient grips. (**e**) Exoskeletons with elastic recovery elements.

Wearable medical devices, characterized by their portability—being compact, lightweight, and easy to transport—can be used by nurses both inside and outside the hospital. Equipped with sensors, these devices can monitor and provide real-time information about posture, promoting proper ergonomics and helping to prevent MSDs. They are especially useful for improving work techniques and reducing exposure to harmful postures [12,14,64–66]. These devices can also collect data to help develop effective prevention protocols [67]. The use of a novel sensor system, including a wearable sensor suit, three-dimensional optical sensors, and electromyography, has been proposed to improve educational processes in the healthcare profession, particularly for nursing students during simulated transfer tasks [68,69].

Wireless and smart devices are also being developed that can monitor workers' posture with feedback to contribute to their safety conditions [70]. It has been proposed to reduce the risk of WMSDs by implementing biomechanical analysis in the activities of greatest risk for nursing staff, in order to relate them to the frequency and time of performance of tasks and to solve the excess of overexertion with the implementation of technological alternatives, devices, or support systems [71].

3.2.6. Information and Communication Technologies

Information and communication technologies (ICTs) have played a crucial role in reducing and preventing musculoskeletal risks among nurses [70] by monitoring and improving postures and movements in the workplace. These technologies can provide real-time feedback, improve ergonomic training, and support injury prevention strategies.

Portable motion capture instruments have the potential to contribute to improved exposure and risk assessment by providing real-time visualization of exposures and automatic analysis, thereby preventing work-related musculoskeletal disorders [72].

A mobile app-based musculoskeletal exercise program for operating room nurses significantly increased self-efficacy and flexibility, while reducing musculoskeletal symptoms and fatigue. The study emphasized that the app provided information on the prevention of musculoskeletal disorders and exercise methods, as well as an opportunity for continuous exercise performance through self-management [73].

Table 3 presents a summary of these alternatives under development, highlighting their primary solutions and potential contributions to improving working conditions in the nursing field.

To facilitate comparison, the technologies mentioned in this section are presented below (Table 4).

Table 3. Summary of the many technological advances, their uses, and most outstanding benefits.

Category	Examples	Benefits
Equipment to Improve Ergonomics	Transfer vests, adjustable workstations, hospital beds with intelligent leveling systems, multifunctional stretchers	Reduce physical effort, especially for nurses, and improve the safety of both staff and patients
Patient Handling Devices	Lifts, transfer devices, multifunctional beds, wall-mounted/mobile workstations, sit–stand seating	Reduce physical strain, lower MSD incidence Mitigate ergonomic stressors
Robotic Systems	Collaborative robotic systems	Reduce physical effort in patient handling
Education in ergonomics	Training on correct techniques, ergonomic assessment protocols	Decrease MSDs, improve safety
Wearable Devices	Sensor-equipped clothing, posture monitoring devices	Maintain good posture, prevent MSDs
Participatory Approaches	Participatory Action-Oriented Training (PAOT)	Practical, low-cost solutions

Table 4. This table provides a comparative analysis of the main technology categories for the prevention of musculoskeletal disorders in nursing staff, summarizing references on approximate cost, typical setting, main preventive effects, and scalability/implementation feasibility.

Technology Category	Approximate Cost	Typical Settings	Main Preventive Effects	Scalability/ Implementation Feasibility
Passive assistive devices (transfer vests, friction-reducing sheets)	Low	Hospitals, long-term care, home care	Reduce peak load on lumbar spine and shoulders during patient transfer	High scalability; minimal infrastructure required
Active exoskeletons/ robotic systems	High	Large hospitals, rehabilitation centers	Reduce lumbar and shoulder muscle activity (25–40%), improve posture control	Limited scalability due to high cost, training, and infrastructure
Wearable sensors and feedback systems	Medium	Hospitals and educational settings	Early detection of poor posture; real-time correction; reduced repetition of high-risk patterns	High scalability; portable and increasingly cost-effective
Adaptive workstations and ICT tools	Low to medium	Clinical documentation areas, nursing stations	Improved ergonomics during prolonged standing/sitting tasks; reduction in neck/upper limb strain	High scalability; low complexity implementation
Training and participatory programs (PAOT, ergonomics education)	Low	All healthcare settings	Improved awareness, safer patient handling, long-term behavioral change	Very high scalability; requires institutional support

Beyond the technical specifications of these devices, the successful implementation of preventive technologies in real-world clinical environments requires addressing multiple practical challenges. Scalability is a critical factor, as complex solutions—such as active exoskeletons or robotic systems—offer substantial biomechanical benefits but often demand specialized infrastructure, additional workspace, and highly trained personnel, whereas portable, low-cost options such as passive exoskeletons, wearable feedback systems, ad-

justable workstations, and mobile applications can be deployed more readily, particularly in resource-limited healthcare settings [74]. Economic considerations also play a decisive role, as high-tech systems entail significant initial investments and ongoing expenses for maintenance, technical support, and software updates, which remain major barriers to large-scale adoption [75], while simpler assistive devices and sensor-based monitoring tools involve lower costs and fewer logistical requirements. Moreover, implementation feasibility depends on adequate staff training, cultural acceptance of new technologies, and the adaptation of workspaces; evidence suggests that pilot programs, ergonomic risk assessments, and participatory strategies involving end users from the earliest stages enhance adoption and sustainability [76]. Addressing these factors is essential to ensure that innovative solutions achieve not only biomechanical effectiveness in controlled environments but also long-term applicability and impact in real clinical contexts.

The Table 5 synthesizes studies addressing intervention, injury reduction, cost savings, and payback period.

Table 5. Comparison between intervention technologies, injury reduction, cost savings, and payback period.

Intervention	Injury Reduction	Cost Savings	ROI Recovery Period
Ergonomic Assessments and Equipment	59.8% reduction in MSD incidence	USD 200,000/year savings	3.75 years [77]
Assistive Devices (Ceiling Lifts, Air-Assisted Devices)	70–71% reduction in hand force	95% reduction in compensation claims	Not specified [78]
Multifaceted Programs (Best Practices)	Significant reduction in injury rates	USD 55,000/year savings	<3 years [79]
General Ergonomic Programs	50% reduction in injury rates	USD 90,000 over 4 months	Not specified [80]

The implementation of technologies and programs to reduce MSDs among nurses generates a significant return on investment (ROI) through decreased injury rates, cost reductions, and improvements in workplace conditions. Multiple studies report reductions of up to 59.8% in MSD incidence and 90% in lost workdays, with investment recovery achieved in less than four years and annual savings exceeding USD 200,000. Interventions such as assistive devices, "no-lift" policies, and multifaceted programs combining ergonomic equipment and training have demonstrated high acceptance, enhanced job satisfaction, and reductions of up to 95% in workers' compensation claims. Cost–benefit analyses and longitudinal evaluations confirm that these programs are not only cost-effective but also sustain their benefits over time.

3.3. Challenges in Implementing Technologies

The implementation of technological solutions to reduce WMSDs in nursing staff can face various limitations and challenges. Among the main barriers identified are personal and contextual factors such as age, level of knowledge about prevention, availability of adequate equipment, workload, staff shortages, and time pressures [81]. These conditions make it difficult to effectively adopt ergonomic strategies in the clinical setting.

In addition, one study reported that both ergonomics awareness and perception of working conditions among nurses were at medium and low levels, respectively. This lack of awareness suggests that the implementation of ergonomic interventions could have a significant impact on reducing occupational injuries, provided that it is accompanied by educational processes and improvements in the work environment [82].

Other limitations that affect solutions to reduce the risk of WMSDs are the lack of compliance by workers to perform activities properly, the scarcity of financial resources

or qualified personnel to implement effective solutions, and the lack of understanding or support from management or organization [44].

Limitations in the implementation of preventive solutions have been identified, including cost, lack of training, insufficient time, and resistance to change [21]. Implementing workplace safety policies can be costly and require significant changes in work organization. Ergonomics education can be effective, but it can be difficult to reach all workers and maintain it in the long term [3].

Applying solutions to reduce the risk of WMSDs may require significant changes in the organization of work or in the work culture, which necessitate time and effort, aspects that many organizations prefer to allocate to other activities of relatively greater importance [44]. Implementing alternative solutions requires efforts on the part of employers and workers; however, solutions will not always be effective for all workers or for all tasks and working conditions and may require adaptations or adjustments to be effective [23].

Superficial studies and a lack of comprehensive research on the long-term use of devices or tools to enhance nurses' working conditions may yield limited, unsound findings with limited applicability to a significant number of nursing professionals [6]. The complexity of the factors contributing to the generation of WMDs necessitates the adoption of comprehensive and participatory approaches that consider psychosocial factors, work organization, and scientific evaluation [3]. Research needs to be individualized and different settings evaluated in order to propose effective interventions and overcome existing limitations in the field of prevention and treatment of these disorders [23,83]. Figure 13 illustrates the most relevant challenges and limitations in the implementation of these technologies to support the work of nursing staff.



Figure 13. Challenges and limitations in the implementation of technologies to reduce musculoskeletal disorders in nurses.

4. Discussion

Nurses face a heightened risk of developing WMSDs due to the highly demanding and physically strenuous nature of their duties. These disorders most frequently affect the lower back, knees, and neck, generating consequences such as chronic pain, muscle fatigue, and circulatory problems, which directly affect absenteeism from work [35]. Evidence indicates that manual handling of loads and repetition of movements are the leading causes of these conditions [20]. In addition, risk factors present in the work environment, such as long hours, lack of preventive measures, inappropriate posture, and staff shortages, all of which increase the likelihood of developing musculoskeletal injuries [19,84].

The consequences of these disorders are not limited to the individual level. From an organizational perspective, its impact is equally considerable. Affected professionals not only experience chronic pain and stress, but also a decrease in their quality of life and functional limitations that compromise their ability to perform their functions effectively [3,5]. As a

result, the quality of care provided to patients may be impaired, as well as the productivity of the healthcare team in general [6].

This scenario was aggravated during the COVID-19 pandemic, when an increase in the prevalence of WMSDs among nursing staff was evidenced. Healthcare overload, shortage of human resources, lack of adequate equipment, and the collapse of health systems were determining factors that intensified exposure to ergonomic risks [39].

Despite the recognition of the problem, there is still an urgent need for further research on the effectiveness of interventions aimed at preventing injuries such as low back pain in this occupational group [35,44]. It is essential to continue developing comprehensive strategies that aim to improve ergonomic and working conditions. An outstanding proposal in this regard is to implement monitoring systems that record the frequency and duration of work activities. This information would allow biomechanical analyses to be carried out that accurately identify the tasks of greatest risk, and with this, design specific and effective solutions to prevent WMSDs in nursing [35].

In this context, several technologies with potential to reduce the risk of injury have been identified, such as ergonomic patient beds and chairs, mobility and lifting assistive devices [78,85], postural monitoring software, and motion tracking tools. In addition, the value of information and communication technologies (ICTs) in automating tasks and reducing repetitive activities is recognized. However, it is cautioned that its implementation must be integrated into a multidimensional approach to ensure its effectiveness [77].

Given that the prevention of WMSDs involves a complex and multifactorial problem, it is recommended to promote continuous and comprehensive research. This must consider, in addition to technological devices, the influence of psychosocial factors such as work stress and the organizational climate. Only through a comprehensive and coordinated approach will it be possible to increase the scope and effectiveness of intervention strategies [6,84].

As a response to RQ1, the tasks associated with the development of MSDs in nurses include patient handling activities such as lifting, transferring, and mobilizing patients; maintaining prolonged static postures; and performing repetitive tasks like writing, typing, administering medications, and documenting medical records. Other contributing factors are extended working hours, sudden or awkward movements in restricted spaces, inadequate use of mechanical equipment without ergonomic training, and hygiene or support tasks requiring physical effort. Psychosocial demands such as stress, time pressure, and lack of rest further exacerbate these risks. These activities, combined with factors like inadequate work surfaces, unsuitable footwear, and individual characteristics, significantly increase the incidence of MSDs, most commonly affecting the lower back, neck, shoulders, knees, and upper extremities.

The findings from the second research question reveal that several technologies have been developed to reduce the risk of WMSDs among nurses by minimizing physical strain and improving workplace ergonomics. These include ergonomically designed equipment, such as adjustable hospital beds, intelligent leveling systems, multifunctional stretchers, and height-adaptable workstations that help to reduce awkward postures and excessive physical effort. Assistive devices, including patient transfer vests, lifting systems, friction-reducing tools, and mobility aids, facilitate safer patient handling and repositioning. Robotic systems, such as collaborative robots, adaptive transfer devices, and wearable exoskeletons, provide direct support during lifting or static holding tasks, significantly lowering physical demands. In addition, wearable technologies equipped with posture-monitoring sensors help to correct harmful movements in real time, while educational and training interventions—often supported by information and communication technologies (ICTs)—improve ergonomic practices, injury prevention, and the effective use of assistive

devices. Collectively, these solutions address key risk factors in nursing tasks, promoting safer work environments and reducing the high prevalence of WMSDs in the profession.

Regarding Research Question 3, the use of assistive solutions in nursing has significant positive impacts on both the prevention and management of MSDs and the overall well-being of nursing personnel. These solutions reduce the physical demands associated with repetitive tasks, awkward postures, and the manual mobilization of patients. By minimizing excessive physical effort and optimizing ergonomics, they help to decrease the prevalence and severity of MSDs, particularly in the lower back, shoulders, and neck. Furthermore, they enhance workplace safety by reducing the risk of falls, slips, and fatigue-related injuries [85], while also improving efficiency and the quality of patient care. When implemented alongside proper training and adequate organizational support, they foster greater job satisfaction, reduce absenteeism, and improve the quality of life of nursing professionals.

To address Research Question 4 regarding the multiple limitations and challenges in the implementation of these technologies, it is important to note that factors such as limited awareness of ergonomics, insufficient training, staff shortages, heavy workloads, time pressures, and resistance to change significantly hinder their effective adoption. Additional barriers include restricted financial resources, a lack of qualified personnel, insufficient managerial support, and the high costs associated with implementing workplace safety policies and organizational changes. Furthermore, these solutions may not be universally effective for all workers or work conditions and often require adaptations to achieve optimal results. The scarcity of long-term, comprehensive research also limits the ability to generalize findings across diverse settings. Overcoming these challenges requires the development of participatory strategies that address psychosocial factors, improve work organization, and promote continuous education, all underpinned by rigorous scientific evaluation.

4.1. Efficiency and Viability of Technologies in the Prevention of WMSDs

The efficacy of technologies aimed at the prevention of WMSDs in nursing workers depends on multiple interrelated factors. One of the most relevant is the ergonomic and functional suitability of the device. Technologies such as transfer vests or self-leveling beds have shown good results when adjusted to the user's anatomy and allow for a balanced distribution of physical loads, reducing effort during critical tasks such as lifting patients [6,49]. This efficacy can be increased if the devices have been designed considering anthropometric characteristics of the nursing staff, most of whom are women [64].

Another essential factor is staff training. Even the most advanced technologies can be ineffective if users are not trained to use them correctly and safely. The document points out that the misuse of assistive devices, such as manual mechanical systems or exoskeletons, can lead to an increase in risk instead of reducing it, especially when it is not accompanied by adequate training in ergonomic techniques [35]. In this sense, educational programs and models such as PAOT have proven to be a key tool to achieve the appropriate use of technologies, favoring their long-term effectiveness [58,59].

In addition, the integration of these solutions into clinical routines directly influences their effectiveness. Some technologies, such as certain active exoskeletons or collaborative robots, although biomechanically efficient, can be disruptive if they are not properly integrated into the clinical workflow or if they require set-up times that make them difficult to use during high-demand situations [2,14]. Effectiveness is also affected by technical and logistical factors such as maintenance, availability of technical support, and durability of equipment. A technology that fails frequently or cannot be kept operational on a continuous basis loses its preventive capacity, especially in environments where resources are limited and specialized technical personnel are not available [44].

Finally, the perception of nursing staff regarding the usefulness, comfort, and safety of technology influences its sustained and correct use. Technologies that are not culturally accepted, that generate discomfort, or that are perceived as barriers in patient interaction, tend to be underutilized, diminishing their real impact on injury prevention. This aspect has been evidenced in studies that show low adherence to ergonomic interventions when they are not accompanied by processes of awareness or active participation of the user [82]. In contrast, the inclusion of staff in the technology adoption process improves their acceptance and commitment, which increases the overall effectiveness of the intervention [58].

Overall, it can be concluded that the effectiveness of these technologies does not lie only in their technical design, but also in their contextualized implementation, in the training of personnel, in their compatibility with hospital dynamics, in operational sustainability, and in the cultural perception they generate in users.

The viability of technologies aimed at the prevention of WMSDs in nursing staff depends on multiple factors that transcend their technical effectiveness. One of the most decisive is the cost of acquiring, installing, and maintaining these devices. Technologies such as active exoskeletons, ceiling lifts, or robotic assistance systems have high levels of biomechanical efficiency; however, they require significant investments that many health institutions are not able to assume, especially in contexts of limited resources [44,51]. This economic limitation conditions its adoption, even in institutions that recognize its preventive usefulness. Active exoskeletons and sensory feedback systems represent emerging technological alternatives with high potential for the prevention of WMSDs in nursing personnel. Unlike passive devices, active exoskeletons provide motorized assistance that reduces lumbar and upper limb load, demonstrating reductions of up to 40% in electromyographic activity and improvements in postural stability. Complementarily, sensory feedback technologies, such as haptic devices and inertial sensors, deliver real-time alerts in response to hazardous postures, facilitating immediate corrections and the adoption of safer movement patterns. However, their effectiveness depends on integration within multifactorial intervention programs that include ergonomic training, institutional safety protocols, and participatory adoption strategies. This underscores the need to implement such interventions through a systemic approach to achieve sustainable impacts in reducing occupational injuries.

Another fundamental aspect is the availability and preparation of human resources. The implementation of ergonomic technologies requires trained personnel who can operate them correctly and safely. The lack of specific training, combined with the work overload that characterizes the hospital environment, makes it difficult to appropriate complex technologies such as collaborative robots or advanced wearable devices [2,14,44]. Even for more accessible tools, such as adjustable workstations or posture sensors, a period of training and adaptation is necessary, which is often restricted by the accelerated pace of clinical work.

Likewise, the physical infrastructure of care units is a factor that can limit the viability of certain technologies. Some devices, such as aerial lift systems or rigid exoskeletons, require wide spaces, structural anchor points, or specific installation conditions that are not always available, especially in older hospitals or in rural areas [51]. The impossibility of adapting clinical environments to the technical demands of this equipment may restrict its use, despite its theoretical benefits.

Viability is also influenced by institutional and organizational factors. In many cases, technologies are not properly integrated due to the absence of clear workplace ergonomics policies, the lack of support from hospital management, or the lack of a culture of prevention. Resistance to change, both by operational staff and at administrative levels, can hinder the adoption of solutions even when favorable technical and economic conditions exist [44,82].

Another relevant element is acceptance by the end user. The perception of comfort, safety, and practical usefulness directly influences the adoption of new technologies. Tools that interfere with patient care, create physical discomfort, or require additional efforts tend to be rejected, regardless of their preventative benefits. In this sense, participatory strategies such as the PAOT model have proven to be effective in improving staff adherence through active inclusion in the identification and implementation of technological solutions [58,82].

Finally, viability increases considerably when technologies are flexible, scalable, low-cost, and easily integrable into the existing clinical flow. Mobile applications for postural self-care, portable monitoring sensors, and mobile workstations represent alternatives that, due to their ease of implementation and low technical requirements, are more feasible in a wide range of hospital settings [8,62,65,79]. The gradual implementation of these solutions, accompanied by continuous training programs, favors not only their operational viability, but also their long-term sustainability.

4.2. Barriers to the Implementation of Technologies in Healthcare Settings

The implementation of technologies aimed at preventing WMSDs in healthcare settings faces several barriers that limit their effective adoption. One of the most significant is the high cost associated with acquiring, installing, and maintaining advanced technologies, such as exoskeletons, ceiling lifts, or robotic systems. These solutions, while proven to be effective, require investments that many institutions, especially in public or rural contexts, are not in a position to undertake [44,51]. Added to this is the scarcity of human resources trained to operate and maintain this type of technology, which compromises its continuous and adequate operation [44].

Organizational barriers also play a significant role. In many care centers, there are no clear policies aimed at ergonomic prevention or established protocols for the integration of technologies into clinical practice. This lack of structure prevents technological solutions from being inserted in a coherent and planned way within the hospital system [82]. In addition, certain devices require physical modifications to the infrastructure—such as additional space, anchor points, or specific electrical connections—that are not feasible in older hospitals or not designed to support modern equipment [51].

At the human level, resistance to change is a frequent limitation. This resistance can manifest itself both in healthcare personnel and at management levels and is usually associated with a lack of knowledge of technology, the perception of discomfort in its use, or the belief that it interferes with the direct relationship between nurse and patient [44,82]. In addition, if staff do not perceive immediate benefits in their daily routine, adherence to their use is likely to decrease, which directly affects the effectiveness and sustainability of the intervention.

Another important barrier is related to training. The absence of continuous training programs limits the correct and safe use of devices, even when they have been correctly implemented. The lack of ergonomic education, combined with work overload, prevents staff from becoming familiar with new technologies, which can lead to misuse or waste of their potential benefits [35,53,56].

Finally, long-term sustainability and impact assessment represent additional challenges. Many of these technologies do not make it past the pilot phase due to the lack of monitoring mechanisms to measure their real effectiveness, their cost–benefit, or their influence on occupational health indicators. Without robust evidence, administrative decisions tend to be conservative, and widespread adoption comes to a halt [21]. In addition, the limited methodological quality of some studies prevents solid conclusions from being drawn about their effectiveness, which affects their credibility and hinders their integration into institutional policies [10].

4.3. Psychosocial Impact of Technology Implementation

The implementation of technologies aimed at the prevention of WMSDs in hospital settings entails not only physical and operational implications, but also relevant psychosocial effects on nursing staff. The introduction of devices such as exoskeletons, wearable sensors, robotic assistance systems, or adjustable workstations may initially lead to uncertainty, anxiety, or resistance, especially when these solutions are implemented without active user participation. These effects are usually related to the fear of change, the perception of substitution of human capabilities, or the interruption of already established work routines [44,82].

However, when technologies are correctly introduced, accompanied by training programs and adapted to the clinical context, they can produce positive effects on the psychological well-being of the worker. The reduction in physical exertion, the lower risk of injury, and the perception of safety offered by technologies such as roof lifts or passive exoskeletons contribute to reducing work stress and increasing the self-confidence of personnel during highly demanding tasks [9,13,49]. These benefits are intensified in scenarios where physical and mental exhaustion is high due to the overload of work and the emotional demands of patient care.

In addition, some wearable technologies, such as smart garments and IMUs, offer immediate feedback on posture and movements, encouraging greater body awareness and facilitating a proactive attitude towards injury prevention. This type of technological assistance, by allowing the user to self-regulate, favors autonomy, commitment to self-care, and a more positive perception of the work environment [62,65,73].

However, psychosocial effects are not always beneficial. The imposition of technologies without adequate support can lead to frustration, resistance, and mental fatigue. This is particularly true when devices are uncomfortable, fail frequently, or generate additional cognitive load by modifying common work procedures. In these cases, technology not only fails to solve the physical problem, but introduces new sources of tension and rejection among users [44].

For this reason, it is essential to consider the emotional, motivational, and relational factors of health personnel when introducing technological innovations. A successful implementation must be based on a participatory approach, with adequate adaptation times, continuous training, and institutional support. Only through a comprehensive strategy that takes into account the psychosocial dimension is it possible to ensure that technology not only reduces biomechanical risks, but also contributes to the overall well-being of the health worker.

4.4. Ethical Consideration in Technological Implementation

The implementation of technologies to prevent WMSDs in the hospital setting requires not only a technical and economic evaluation, but also a rigorous ethical analysis. One of the first aspects to consider is the principle of justice, which requires guaranteeing an equitable distribution of technological resources among all personnel exposed to biomechanical risks. In many settings, devices such as exoskeletons, patient lifts, or adjustable workstations may be available only for certain shifts or areas, leading to inequality and potential strains within the work team [44].

In addition, worker autonomy is a central ethical principle that can be compromised when the introduction of technologies is carried out without consultation or active participation of staff. The imposition of devices without considering the users' opinions, perceptions, and experiences can generate rejection, anxiety, and a sense of depersonalization of care work. Evidence has shown that a lack of awareness or involvement in the process of

technological implementation is associated with low adherence and adverse psychosocial effects, such as frustration or increased work stress [44,82].

The principle of nonmaleficence must also be carefully evaluated. Some devices, if not properly designed, adjusted, or used, can produce new physical discomfort, interfere with natural movement, or even aggravate existing musculoskeletal conditions. In addition, an inadequate introduction of technologies can generate cognitive overload, reduce the perception of control, or alter the human bond between nurse and patient, which represents both a physical and emotional risk [9,13,49].

Data protection and worker privacy is another relevant ethical axis, especially in the face of the growing use of wearable sensors, smart garments, or connected technologies that collect information on posture, movements, and performance. It is essential to ensure that the data collected are used exclusively for preventive, educational, or ergonomic purposes and that they do not become tools for surveillance or labor control. The implementation must comply with confidentiality standards and ensure that the worker is informed about what information is collected, how it is stored, and for what purpose [62,65,73].

Finally, for the implementation of technologies in hospital settings to be ethical, it must be built on a participatory and person-centered approach. This involves integrating staff from the initial phases of selection, testing, and validation, ensuring adequate training processes and establishing protocols that prioritize the dignity, safety, and integral well-being of those on the front line of care. Only through this comprehensive view can it be ensured that technological development not only prevents injuries, but also respects the fundamental values of professional ethics and health care [44,82].

5. Future Directions

From a broad theoretical perspective, the evolution of technologies for preventing WMSDs in nursing demonstrates a clear shift from simple mechanical solutions—such as adjustable workstations and manual transfer devices—to integrated, intelligent systems. Over the past decade, the introduction of robotic assistance, wearable exoskeletons, and sensor-based feedback has enabled real-time monitoring of posture and workload. More recently, the convergence of artificial intelligence, data analytics, and ergonomic risk modeling has led to adaptive interventions capable of anticipating and preventing hazardous movements.

Future strategies are expected to focus on integrating these technologies within organizational frameworks that combine technical devices, continuous ergonomic training, and a strong safety culture. Key priorities include the development of lightweight, cost-effective exoskeletons for healthcare environments; AI-powered wearable systems for personalized feedback; and longitudinal studies assessing both physical and psychosocial impacts. This comprehensive approach aims to transition from reactive models to proactive, data-driven, and sustainable prevention.

Technological development has taken on an increasingly important role in the prevention of MSDs in nursing staff, one of the professions most affected by injuries derived from physical exertion and manual handling of patients. As the impacts of these conditions on the health of the worker and the quality of care provided are recognized, new lines of research are emerging aimed at innovation and continuous improvement of ergonomic interventions and care equipment.

Ongoing research is critical to designing, optimizing, and validating technologies that effectively prevent musculoskeletal injuries. This work involves not only the development of new ergonomic devices and robotic assistance systems, but also the improvement of training programs that integrate the proper use of these tools. The long-term evaluation

of the clinical and occupational benefits of these technologies is crucial to ensure their effectiveness and sustainability over time [4,5].

The successful implementation of preventive technologies requires processes of systematic evaluation and contextual adaptation. It is essential to ensure that such strategies respond to the real needs of health personnel, improve clinical outcomes, and do not introduce new risks or operational burdens. The approach must be comprehensive, considering technical, human, and organizational aspects that can influence effective adoption [7,19].

Among the solutions currently used are technical patient handling equipment, such as lifts and transfer devices, which have been shown to significantly reduce the risk of MSDs in nursing staff. In addition, there are safe patient management programs, which combine continuous training with technological integration to reduce the incidence of work-related injuries [6,10,11].

Emerging technologies, on the other hand, include automated systems, postural monitoring sensors, and collaborative robots that not only help in the physical management of patients, but also contribute to the rehabilitation process and improve clinical outcomes [8]. Evidence suggests that these systems could generate favorable returns on investment and sustained benefits in terms of occupational health [11].

Despite progress, significant challenges remain. The efficacy of some devices is still debated due to the limited methodological quality of the available studies [10]. In addition, the increase in overweight or obese patients poses additional challenges, which require more robust technologies adapted to complex clinical conditions [9]. Staff acceptance, acquisition cost, required training, and organizational barriers are also barriers that need to be addressed through comprehensive institutional policies.

Multifactorial programs that integrate technology, scientific evidence, andsafety practices have achieved statistically significant reductions in the rate of musculoskeletal injuries and in injury-modified workdays [13]. However, it is also necessary to consider the potential risks for patients, which requires responsible implementation, which takes into account human, technological, and structural factors to avoid adverse events [12].

The future of musculoskeletal risk prevention in nurses will depend on the convergence of advanced technology, continuing education programs, and sound organizational policies. The key to moving forward lies in an interdisciplinary strategy, which not only incorporates effective technical solutions, but also ensures their safe adoption and adapted to diverse clinical settings. Research and development will continue to be essential pillars to face emerging challenges and ensure safer, healthier, and more efficient work environments for nurses.

6. Conclusions

Nurses face an elevated risk of developing WMSDs, due to the demanding nature of their duties, which include manual handling of loads, repetitive movements, and constant exposure to improper postures. These factors, combined with adverse working conditions such as long hours, lack of preventive measures, and staff shortages, generate significant impacts on both the health of the worker and the efficiency of the health system. The most affected anatomical regions include the lower back, knees, and neck, with consequences ranging from chronic pain and fatigue to a decrease in quality of life and professional performance.

From an organizational perspective, WMSDs represent a direct threat to the quality of care provided and to the productivity of the healthcare system. This scenario was aggravated during the COVID-19 pandemic, in which care overload and the lack of human and material resources accentuated ergonomic risk factors. This evidenced the urgency of establishing sustainable preventive strategies adapted to contexts of high demand.

Although various technological solutions have been proposed, such as ergonomic devices, postural monitoring technologies, and assistive tools for lifting and mobility, their real impact depends on a comprehensive implementation that also considers psychosocial and organizational factors. ICT can play a key role in automating repetitive tasks and collecting useful data for ergonomic analysis.

In this sense, it is recommended to develop future research that addresses the effectiveness of technological interventions in the long term, as well as studies that analyze the role of the work environment, stress, and organizational culture in the prevention of WMSDs. Likewise, it is essential to promote the design of continuous monitoring systems that allow for real-time evaluation of working conditions and accurate biomechanical analyses. This would facilitate the development of specific, science-based solutions aimed at improving the occupational health of nursing staff.

Finally, it is necessary to promote interdisciplinary and collaborative approaches that include health professionals, engineers, designers, and institutional managers. Only through an articulation of knowledge and efforts will it be possible to move towards safer, more efficient, and sustainable work environments in the nursing sector.

Despite significant advancements in the development of integrated and intelligent technologies for the prevention of work-related musculoskeletal disorders in nursing, several critical aspects remain insufficiently addressed in the current literature. There is a marked lack of research on the economic feasibility and scalability of these solutions, particularly in low- and middle-income healthcare systems, where resource constraints may impede their implementation. Similarly, the ethical and privacy implications of continuous biomechanical and physiological monitoring especially when enabled by AI-powered wearable devices are seldom examined in depth. Evidence is also limited regarding the cultural and organizational factors that influence the acceptance and sustained adoption of these technologies, as well as strategies to ensure inclusivity for diverse user populations with varying physical capabilities. Addressing these gaps will be essential to ensure that future preventive models are not only technologically advanced, but also equitable, ethically responsible, and adaptable to a wide range of healthcare contexts.

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Abbreviations

The following abbreviations are used in this manuscript:

MSDs	Musculoskeletal disorders
WMSDs	Work-related musculoskeletal disorders
SDGs	Sustainable development goals
PARiHS	Promoting Action on Research Implementation in Health Services

RQ	Research question
ARNA	Adaptive robotic nurse assistant
PAOT	Participatory action-oriented training
LBP	Low back pain
ICTs	Information and communication technologies

Appendix A

Table A1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMAScR) Checklist.

Section	Item	PRISMA-ScR checklist item	Reported on Page#
		Title	
Title	1	Identify the report as a scoping review.	1
		ABSTRACT	
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
		Abstract	
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	1–3
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	6
		Methods	
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a web address); and if available, provide registration information, including the registration number.	6
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status) and provide a rationale.	8, 9
Information sources *	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	8
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	6
Selection of sources of evidence †	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	6
Data charting process ‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was performed independently or in duplicate) and any processes for obtaining and confirming data from investigators.	-

Table A1. *Cont.*

Section	Item	PRISMA-ScR checklist item	Reported on Page#
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	-
Critical appraisal of individual sources of evidence §	12	If performed, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	-
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	-
		Results	
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	21
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	-
Critical appraisal within sources of evidence	16	If performed, present data on critical appraisal of included sources of evidence (see item 12).	-
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	-
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9–22
		Discussion	
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	23-25
Limitations	20	Discuss the limitations of the scoping review process.	25
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	24–26
		Funding	
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	26

J.B.I. = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews. * Where sources of evidence (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and websites. † A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with information sources (see first footnote). ‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the J.B.I. guidance (4, 5) refer to the process of data extraction in a scoping review as data charting. § The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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