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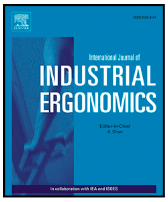

Review of upper-limb occupational exoskeletons: From technology to assessment

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ABSTRACT

Occupational exoskeletons are emerging as a promising solution to reduce work-related musculoskeletal disorders (MSDs) across various industries. Upper-limb exoskeletons are particularly relevant, given the high prevalence of MSDs associated with repetitive arm motions and overhead tasks. However, evaluating the effectiveness of these devices requires careful analysis of the specific technologies and kinematic designs they incorporate to ensure their safe and effective integration. This paper presents a detailed technological review and analysis of the existing literature, focusing on the diversity of technologies and the need for more comprehensive studies addressing challenges in both laboratory and real-world settings. This study particularly highlights the necessity of assessments that account for the unique characteristics of different exoskeleton technologies, rather than generalizing across them. It also emphasize the need to examine not only reductions in muscle activity but also the potential for overlooked side effects, long-term impacts, and adaptations across different task types. These factors are crucial, as upper-limb exoskeletons are planned to be deployed for prolonged use in complex industrial environments.

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1. Introduction

Work-related Musculoskeletal Disorders (MSDs) represent a significant occupational health concern, particularly in industries requiring repetitive and strenuous tasks such as automotive manufacturing. MSDs are among the leading causes of disability, absenteeism, and productivity loss, with the upper limbs, especially the shoulders, being the most affected (Punnett and Wegman, 2004; Rijn et al., 2010; Molen et al., 2017). These disorders often stem from repetitive overhead tasks, leading to increased interest in ergonomic interventions to mitigate these risks.

Traditionally, ergonomic tools and practices, including manipulators and industrial robots, have been used to reduce the need of human operators in tedious tasks. However, the rapid advancement of wearable technology has introduced a new solution: occupational exoskeletons. These devices, designed to be worn by workers, offer support to the musculoskeletal system, particularly the upper limbs, by reducing the physical load during demanding tasks (Botti and Melloni, 2023; Crea et al., 2021). Occupational exoskeletons are increasingly recognized as a potential solution to prevent work-related MSDs, particularly in sectors where workers are exposed to excessive repetitive tasks, non-neutral postures, and heavy lifting (Torricelli et al., 2020; De Looze et al., 2016).

Since MSDs and fatigue frequently impact the lower back and shoulders (Umer et al., 2018; Hussain, 2004; Afonso et al., 2014; Parent-Thirion et al., 2016), many exoskeletons are designed to support these areas. This review therefore focuses on these devices, which are expected to play a key role in reducing injury risks in industrial settings involving repetitive arm movements.

Exoskeletons can be broadly categorized into passive, active, and hybrid (semi-passive) systems, as well as by their kinematic structure. Passive exoskeletons, which rely on mechanical elements like springs or counterbalances to redistribute forces, have gained popularity due to their simplicity and affordability (Maurice et al., 2020). Active systems, on the other hand, incorporate motors or pneumatic actuators to provide powered assistance, offering more dynamic support but at the cost of increased complexity and weight (Zhou and Zheng, 2022). Hybrid systems aim to combine the advantages of both but face challenges in adoption due to complexity and cost (Grazi et al., 2020). Additionally, exoskeletons can be classified based on their kinematic structure: rigid (either anthropomorphic or non-anthropomorphic) and soft. Rigid exoskeletons provide structural support through durable frames, whereas soft exosuits offer flexibility and comfort, being lighter and more adaptable but providing less support and generating less torque. An overview of the existing solutions is reported in Fig. 1.

Beyond individual sectors, the development and adoption of occupational exoskeletons are progressing at a global scale. In Europe, initiatives in the automotive and aerospace industries have driven early adoption, supported by EU-funded projects such as Robo-Mate and WearHap, which aim to enhance workplace ergonomics and reduce musculoskeletal risks (De Looze et al., 2016; Altenburger et al., 2016; Torricelli et al., 2020). North America has seen parallel advancements, with pilot programs in logistics, construction, and defense sectors where reducing physical strain and associated injury costs has been a strong economic motivator (Kim et al., 2021; Schmalz et al., 2019; Zhou and Zheng, 2022). In Asia, particularly Japan and South Korea, exoskeletons start being considered not only in manufacturing but also in healthcare and elderly care, reflecting demographic challenges and workforce sustainability needs (Crea et al., 2021; Botti and Melloni, 2023; Tian, 2024). Meanwhile, countries such as China and India are exploring industrial and agricultural applications, where repetitive manual labor remains prevalent and injury prevention carries major socioeconomic implications (Iranzo et al., 2020; Nassour et al., 2021; Zhou et al., 2024).

This growing global interest underscores that occupational exoskeletons are not confined to specific regions or industries but are increasingly viewed as a universal ergonomic solution. However, the diversity in industrial contexts, workforce demographics, and regulatory frameworks means that their effectiveness and acceptance may vary widely, further highlighting the need for comprehensive, cross-contextual evaluations such as the one presented in this review (Ahmad et al., 2024; Moeller et al., 2022; Flor-Unda et al., 2025).

Despite the promising potential of those exoskeletons, their widespread adoption in real-world scenarios remains limited. This is due to the lack of clinical proof of their effectiveness, resulting from the diversity in their technological designs, which complicates the standardization of evaluation methods. Most existing studies have focused on the immediate benefits of these devices, such as reducing muscle activity and fatigue during specific tasks (Bock et al., 2022; Schmalz et al., 2019). However, there is a growing recognition of the need to assess their long-term effects, including potential side effects, impacts on unsupported body regions, and changes in movement patterns and motor control strategies over prolonged use (Crea et al., 2021; Proietti et al., 2017; Ramella et al., 2024).

Current research is predominantly conducted in controlled laboratory settings, necessary for initial assessments but insufficient to replicate the complexity of real-world industrial environments and scenarios of use. In actual workplaces, workers perform a range of movements and transitions between tasks, significantly influencing the effectiveness and ergonomics of exoskeletons (Moeller et al., 2022). The lack of comprehensive in-field studies that evaluate both the intended and unintended consequences of exoskeleton use over long durations highlights a critical gap in the literature (Iranzo et al., 2020; Kim et al., 2021).

Occupational exoskeletons are the subject of numerous review articles in the literature. Table 1 summarizes the most recent review articles on occupational upper-limb exoskeletons, analyzing their main themes, conclusions, technological focus, and assessment approaches in order to highlight their specific contributions to the state of the art.

A first cluster of works addresses risks, long-term effects, and user well-being. Cardoso (Cardoso et al., 2024) demonstrates that the majority of studies are short-term, with discomfort, restricted motion, and limited real-world transferability still unresolved. Flor-Unda et al. (2025) emphasizes the absence of longitudinal evaluations and cautions against the physiological and ergonomic side effects of protracted use. The imperative need for long-term, field-based assessments is underscored by Moeller et al. (2022), who also emphasize the variability between laboratory and workplace findings.

A second thematic area concerns technological design, mechanisms, and anatomical specificity. Supriyono (2025) reviews elbow exoskeletons, identifying engineering trade-offs in mechanical and actuation design, while Tian (2024) focuses on shoulder exoskeletons, demonstrating their benefits in overhead work but noting limitations in versatility, comfort, and control. Ashta et al. (2023) concentrates on passive devices in manufacturing and logistics, underlining their utility for static tasks but also their shortcomings in dynamic applications and adoption challenges.

A third set of reviews pertains to intention prediction and control strategies. Hochreiter (2025) emphasizes the technical challenges in

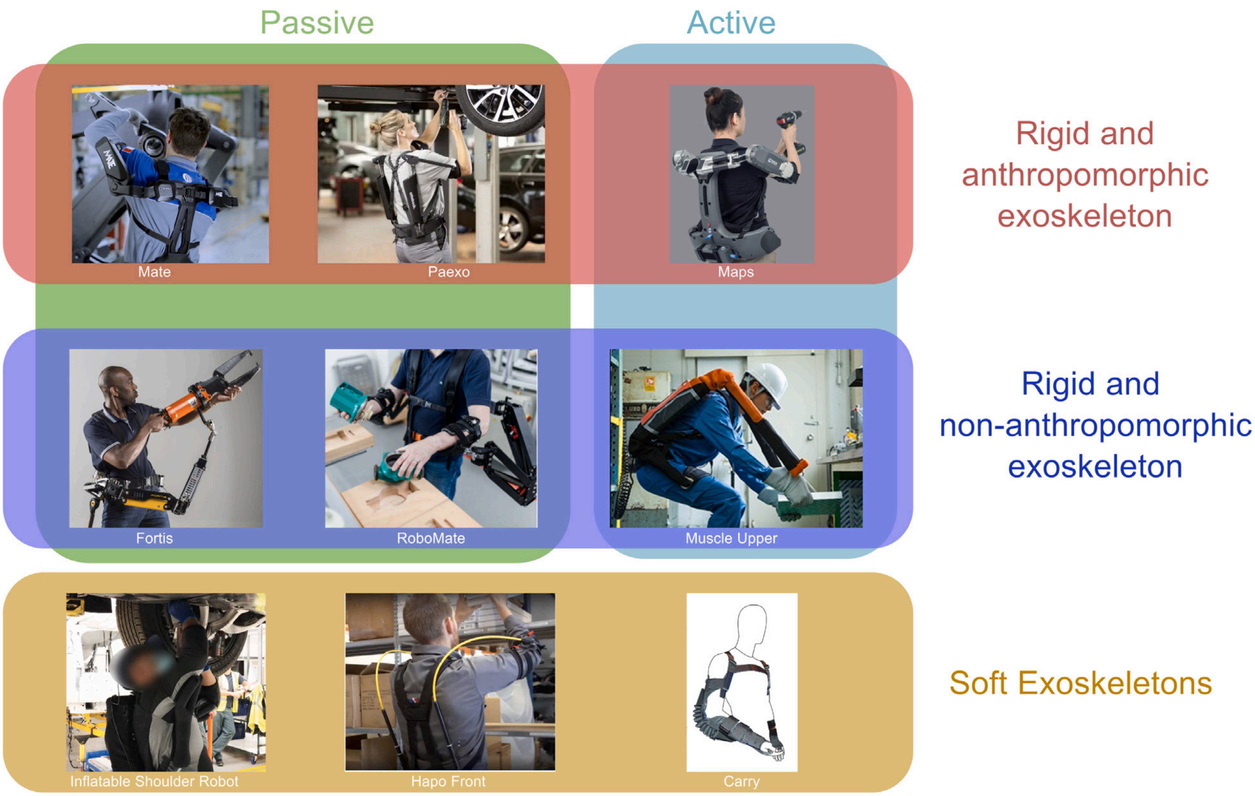

Fig. 1. Classification of the different types of exoskeletons included in this review Rigid anthropomorphic exoskeleton: Mate (Pacifico et al., 2022), Paexo (Maurice et al., 2020), Maps/Rigid non-anthropomorphic exoskeletons: Fortis (Chambers et al., 2016), RoboMate (Altenburger et al., 2016), Muscle Upper/Soft Exoskeletons: Inflatable Shoulder Exo (Zhou et al., 2024), Hapo Front (Tellier et al., 2021), Carry (Nassour et al., 2021).

robustness and usability, as well as the absence of standardized evaluation and large-scale field validation, in his survey of sensor-based and machine-learning approaches to active exoskeleton control.

A fourth group emphasizes assessment frameworks and methodological consistency. De Bock et al. (2022) propose benchmarking approaches to overcome the heterogeneity of protocols, advocating the integration of both objective and subjective measures. Ahmad et al. (2024) introduce a Technology Readiness Level (TRL)-based framework, mapping how evaluation priorities evolve from early prototypes to market-ready systems and workplace integration.

Finally, Ahmad et al. (2024) address the market and adoption perspective by mapping 132 models from 72 companies worldwide. Their findings demonstrate that industrial adoption is dominated by passive exoskeletons and identify voids in under-served sectors, such as construction. Collectively, these evaluations offer a multifaceted perspective on the current landscape, including technological diversity, anatomical focus, control strategies, methodological standardization, market dynamics, and user-centered risks.

While existing reviews have provided valuable insights into adoption frameworks (Ahmad et al., 2024), sustainability aspects (Ashta et al., 2023), benchmarking evidence (De Bock et al., 2022), market dynamics (Al-Khiami et al., 2024), or specific subsets of devices such as shoulder (Tian, 2024) and elbow exoskeletons (Supriyono, 2025), they often focus on isolated perspectives. For instance, Supriyono (2025) provide an in-depth analysis of sensors and actuation technologies across upper-limb exoskeleton designs, highlighting structural diversity for elbow devices, while Tian (2024). However, few works explore in detail the technological diversity and kinematic structures across the broad range of upper-limb exoskeletons, and even fewer address the long-term effects, potential side effects, and overall impact on workers' health and performance in real-world industrial contexts. Compared to the reviews summarized in Table 1, the present work makes a distinctive contribution by bridging two dimensions that are often treated separately: the technological diversity and kinematic structures of upper-limb exoskeletons and their evaluation in terms of human effects. Although most existing reviews have focused on specific aspects, such as long-term risks and side effects (Flor-Unda et al., 2025; Cardoso et al., 2024; Moeller et al., 2022), device typologies and anatomical focus (Supriyono, 2025; Tian, 2024; Ashta et al., 2023), intention prediction and control strategies (Hochreiter, 2025), methodological frameworks (De Bock et al., 2022; Ahmad et al., 2024), or market trends (Al-Khiami et al., 2024), few have offered an integrated perspective that jointly evaluates how design choices influence user outcomes. This review explicitly connects the analysis of mechanisms, actuation systems, and kinematic compatibility with the assessment of physiological, ergonomic, and experiential effects on workers. By doing so, it not only characterizes the technological diversity of occupational exoskeletons but also evaluates their real-world implications for health, comfort, and performance, thus filling a critical gap in the current literature and offering guidance for both developers.

This paper aims to characterize these gaps by providing a review of upper-limb occupational exoskeletons, with a particular focus on the technological diversity and kinematic structures of these devices. We will also explore the current state of research on their long-term effects, side effects, and overall impact on workers' health and performance in real-world settings. Through this analysis, we seek to contribute to a more nuanced understanding of the benefits and limitations of exoskeletons, ultimately informing their development and integration into industrial practices.

Given the rapid advancements and the increasing number of patents in industrial ergonomics, this review does not claim to be exhaustive in listing all the developed solutions. Instead, it focuses on presenting the state of the art by studying the main features and specific characteristics of available upper-limb exoskeletons. Additionally, this review evaluates the methodologies used to assess these devices, with a focus on secondary outcomes, such as the long-term effects and performance in non-specific tasks. The rest of the paper is structured as follows: first, the research strategy is outlined; next, a comprehensive list of the devices found in the literature is presented, together with the publications about the topic; finally, the adopted solutions and their broader implications are discussed.

2. Materials and methods

2.1. Sources and keywords

The bibliographic research was conducted with a comprehensive approach to gather relevant studies and patents on upper-limb exoskeletons designed for occupational use. The primary databases used for this search were PubMed and Scopus, selected for their extensive coverage of biomedical and engineering literature. The search specifically targeted studies evaluating exoskeletons developed or utilized in workplace settings, regardless of their operational mode—be it active, passive, or hybrid. Exoskeletons focused primarily on other body parts, such as the back, legs, or hands, were excluded unless they provided dual support for both the upper limbs and other regions like the back or legs. Rehabilitation exoskeletons were also excluded from this review, as the primary interest was on devices intended to assist with occupational tasks rather than therapeutic interventions. Including back-, leg-, or hand-focused exoskeletons would have substantially broadened the scope of this review, shifting it toward a general overview of occupational exoskeletons rather than a targeted analysis of upper-limb devices. Their inclusion would have diluted the depth of discussion on technological diversity and kinematic structures specific to upper-limb applications, which are the central objectives of the present work. To ensure consistency and relevance, only studies published in english were considered.

The literature search was conducted between April and May 2024. A combination of keywords was used to identify relevant studies and patents. The search terms included: `exoskeleton` AND (`active` OR `passive` OR `work*` OR `hybrid` OR `job` OR `occupation*` OR `overhead`). These terms were selected to encompass a wide range of exoskeleton types and their applications in occupational settings. To broaden the scope and identify additional devices, further research was conducted using online databases and repositories, such as Exoskeleton Report, which specializes in exoskeleton technology and provides detailed insights into various commercially available and prototype devices.

2.2. Eligibility criteria

The eligibility criteria for selecting studies on upper-limb exoskeletons in workplace settings are depicted in the scheme of Fig. 2. Studies were included if they focused on exoskeletons designed for or used in occupational environments, provided empirical data on the performance and effects of these devices, and addressed both the technological aspects and ergonomic implications of exoskeleton use. Conversely, studies were excluded if they primarily focused on exoskeletons designed for back, leg, or hand support without upper limb assistance, were centered on rehabilitation or medical applications, or lacked experimental data, relying instead on purely theoretical discussions. Fig. 2 provides a visual summary of the decision-making process used to determine study eligibility.

2.3. Data screening

The initial search yielded a large number of studies, which were then screened in two stages:

1. Title and Abstract Screening: This initial screening phase involved a review of titles and abstracts to eliminate irrelevant studies.
2. Full-Text Review: Studies that passed the initial screening were subjected to a full-text review to ensure they met the inclusion criteria and provided sufficient empirical evidence.

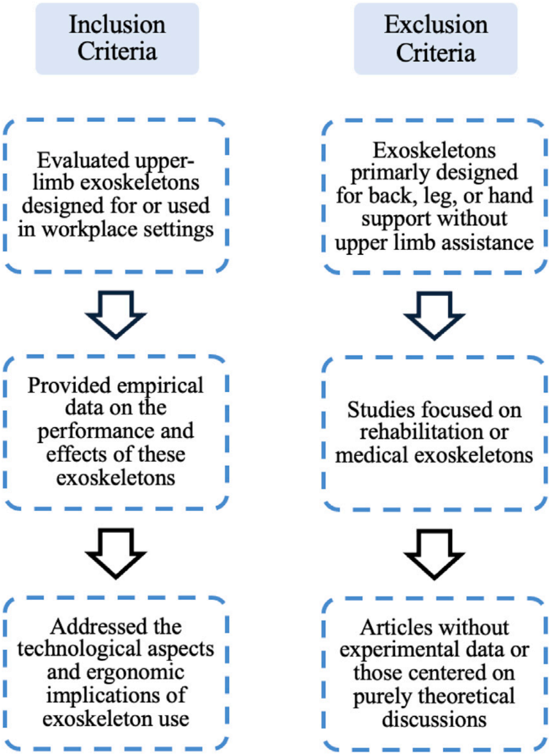

Fig. 2. Eligibility criteria for selecting studies on upper-limb exoskeletons in workplace settings.

The 59 studies that met the inclusion criteria were analyzed to extract key information, including the type of exoskeleton, its kinematic structure, actuation methods, and the specific occupational tasks it was designed to assist with. Particular attention was paid to the methodologies used to evaluate these exoskeletons, the outcomes reported, and any long-term effects or side effects noted.

The overall method and process to include studies in this review can be seen in Fig. 3.

3. Results

The two tables (2, 3) provide a comprehensive overview of upper-limb exoskeletons used in occupational settings, focusing on different aspects of analysis. Table 2 details the technical specifications of the exoskeletons, including power source, kinematic structure, attachment points, supported body parts, primary tasks, weight, and peak torque. This table allows for a comparison of the mechanical and functional attributes of each device, highlighting their intended applications and physical characteristics. The Table 3 shifts the focus to the evaluation of these devices in terms of their effects on users. It includes information on the studies conducted, the evaluation of side effects, the presence or absence of after-effects, long-term evaluations, and unassisted body areas. This table emphasizes the types of research carried out on these exoskeletons.

4. Discussion

Research on exoskeletons has seen significant growth in recent years, as shown in Fig. 4, with the number of published studies increasing dramatically since 2018. These findings are consistent with

Table 1

Comparative summary of recent review literature on occupational upper-limb exoskeletons.

Author (Year)	Main themes reviewed	Main conclusions	Technological aspects	Assessment aspects
Flor-Unda et al. (2025)	Adverse effects due to the prolonged use of upper-limb exoskeletons	• Lack of longitudinal studies and real-world evaluations • Limited transferability of lab results to actual work conditions • Need for extensive field testing on sustainability, health impact, and workflow integration • Absence of design/safety standards and effective training programs	**Technological diversity** NA* **Kinematic structure** NA	**Long-Term Effects** Considers risks of prolonged use (muscle overload, fatigue, joint stress, cardiovascular cost) **Side Effects** In-depth (physiological, psychological, technological/ergonomic) **Real-World Health Impact** lab vs. field studies, emphasizes workplace risks and standards
Supriyono (2025)	Mechanical designs, actuation systems, control approaches, and applications of elbow exoskeletons, with focus on design trends, effectiveness, and research gaps for practical and accessible solutions	• Focus mainly on flexion–extension; Limited integration of supination–pronation • Engineering trade-offs in size, weight, and usability when adding more DoF • Balance between precision and usability not always achieved • Technical issues: user intention detection (EMG), power autonomy, sensor stability, actuator efficiency • High user variability requires adaptable and modular solutions	**Technological diversity** Classifies elbow exoskeletons by mechanical structure, actuation, sensing **Kinematic structure** Detailed elbow kinematics	**Long-Term Effects** NA **Side Effects** NA **Real-World Health Impact** Adoption challenges shortly addressed
Hochreiter (2025)	Systematic review (2007–2024) on intention prediction methods for active upper-limb exoskeletons in industrial settings, analyzing sensor-based, machine learning, and hybrid approaches, with implications for ergonomics, usability, safety, and real-time control	• Lack of standardized evaluation protocols and comprehensive metrics • Scarcity of real-world industrial validations beyond laboratory settings • Limited robustness, generalizability, and diversity of participant samples for tests • Technical challenges in balancing accuracy, response time, and computational cost • Need for multimodal data fusion and advanced AI-driven adaptive control for scalability and user acceptance	**Technological diversity** Intention prediction methods, sensors and control strategies **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** Only minor notes on assessment of usability and effectiveness **Real-World Health Impact** No field studies analyzed
Cardoso et al. (2024)	Systematic review (2014–2024) on the use of exoskeletons for the prevention of work-related musculoskeletal disorders (WMSDs) in occupational settings. The authors analyze applications across various industries, evaluating ergonomic outcomes, task performance, and worker well-being	• Most studies are lab-based with small samples, short-term studies, lacking large-scale and real-world evaluations • Research focuses mainly on passive exoskeletons, back/upper-arm support, and overhead/lifting tasks, leaving other devices, body parts, and occupational scenarios underexplored • Objective measures (EMG, kinematics) dominate, while observational approaches and comprehensive integration of subjective user experience are underused • Persistent issues of discomfort, task incompatibility, restricted motion, and usability concerns remain insufficiently addressed	**Technological diversity** Covers active vs. passive and body-region devices **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** Notes discomfort and ergonomic issues **Real-World Health Impact** Study context is analyzed
Ahmad et al. (2024)	Systematic review and conceptual framework linking exoskeleton adoption to Technology Readiness Levels (TRLs); maps current evidence on ergonomics, usability, productivity, and health outcomes; shows how these dimensions are assessed differently as devices evolve—from laboratory prototypes (focused on ergonomics and basic functionality) to market-ready systems(evaluated in terms of usability, workplace integration, and long-term impact on worker health and productivity)	• Exoskeletons reduce muscle activity and WMSD risk, with generally positive user feedback • Research is concentrated in manufacturing/automotive; other high-risk sectors are underexplored • Assessments rely mainly on EMG and questionnaires; other metrics are rarely used • Need for systematic TRL-based evaluation, longer trials, larger samples, and broader device/sector coverage	**Technological diversity** Covers TRL stages, device typologies **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** It is focused on muscles activations in the supported area, and then user comfort and acceptance, the overall body impact is not considered **Real-World Health Impact** Includes industrial scenarios and in-depth analysis

(continued on next page)

Table 1 (*continued*).

Al-Khiami et al. (2024)	Overview of the exoskeleton industry, mapping current market dynamics, technological developments, application domains, and adoption trends	• 132 models from 72 companies worldwide; rapid market growth • Industrial use dominates, but devices are not sector-specific • Passive types prevail in industry; active in healthcare • Construction sector underserved, showing clear gap for tailored solutions	**Technological diversity** Industry trends and market diversity; covers active vs. passive **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** NA **Real-World Health Impact** Notes industry adoption impact
Tian (2024)	Occupational shoulder exoskeletons for industrial use, analyzing mechanical designs, actuation systems, control strategies, and evaluation methods	• Shoulder exoskeletons lower muscle load and WRMSD risk in overhead work • Market devices are mainly passive/rigid; soft and active types still face weight, cost, and control issues • Current assistance is limited to gravity compensation; more versatile support is needed • Evaluation remains short-term and non-standardized; long-term field studies are lacking	**Technological diversity** Mechanism design, actuators, control of shoulder devices **Kinematic structure** Analyzed, with a focus on kinematic compatibility	**Long-Term Effects** NA **Side Effects** Mentions discomfort/fit issues **Real-World Health Impact** Some real-world assessment noted
Ashta et al. (2023)	Passive exoskeletons in manufacturing and logistics, assessing their performance across tasks, evaluation methods, efficiency and cost, and proposing a maturity map and future research agenda for industrial adoption	• Passive exoskeletons help in static tasks but less in dynamic ones • Adoption limited by discomfort, fit, and acceptance issues • Evidence mostly from labs; real-world and long-term data are scarce • Standardized evaluation and regulation still needed	**Technological diversity** Focus on passive exoskeletons in manufacturing and logistics **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** Mentions comfort/acceptance **Real-World Health Impact** Discusses efficiency and cost in real-world manufacturing and logistics
De Bock et al. (2022)	Occupational exoskeletons, classifying assessment types and methods, and proposes a framework to benchmark devices for more consistent, comparable, and user-centered evaluation	• Exoskeleton assessment is a dynamic process, evolving from controlled validation to applied field studies • Heterogeneity of protocols limits comparability across devices and studies • A benchmarking framework is needed to align methods and improve consistency • Future research should combine objective and subjective measures and expand field evaluations for real-world relevance	**Technological diversity** Distinguish between active and passive exoskeletons in the analysis **Kinematic structure** NA	**Long-Term Effects** NA **Side Effects** Perceived exertion, discomfort, obstruction, pressure points, workload, usability. The evaluation of side effects relies mainly on subjective measures (questionnaires, scales, self-reports). **Real-World Health Impact** Field studies on ergonomics, muscle activity, fatigue, productivity, and acceptance in actual work settings
Moeller et al. (2022)	Upper-limb exoskeletons for occupational use, analyzing design types, supported tasks, and evaluation methods (objective and subjective) with emphasis on shoulder-support devices	• Upper-limb exoskeletons can reduce muscle activity and perceived exertion, mainly in overhead tasks • Benefits are clearer in lab settings; field results are more variable • Discomfort, limited motion, and usability issues remain barriers to adoption • More long-term and real-world studies are needed to confirm health and productivity impacts	**Technological diversity** Considers a wide variety of upper-limb exoskeletons (active, passive, semi-passive), mostly shoulder-support devices **Kinematic structure** Kinematic outcomes such as joint angles, ROM, posture deviations, and COP (center of pressure) are systematically analyzed	**Long-Term Effects** NA **Side Effects** Changes in posture and kinematics, perceived exertion and workload, discomfort, pain, and usability issues **Real-World Health Impact** Reduction of muscle activity, productivity and task performance, user acceptance and intention to use

those of Moeller et al. (2022), who reported that 32 out of 35 studies published between 2014 and 2022 appeared in the last four years. This trend is also reflected in review articles such as De Bock et al. (2022) and Ahmad et al. (2024), which mapped an accelerating evidence base. This surge in research interest parallels the expansion of the exoskeleton market. The global exoskeleton market size is projected to grow at a Compound Annual Growth Rate (CAGR) of 16.6% from 2024 to 2030, driven by innovations in powered exoskeleton technologies and their increasing adoption across various sectors, including manufacturing and construction (ICTMedia, 2023).

4.1. Technical specifications

This first part of the discussion will focus on technical and design specifications of the exoskeletons presented in Table 2.

4.1.1. Passive exoskeleton predominance

The majority of industrial exoskeletons are passive (Fig. 5, created from data in Table 2), a trend consistent with prior observations (De Looze et al., 2016). This predominance is also confirmed in multiple empirical studies evaluating devices such as the Airframe (Kong et al., 2023; Gillette et al., 2022; Groos et al., 2022; Masood et al., 2022; Schwerha et al., 2021; Rubenstone, 2019; Spada et al., 2017; Weston et al., 2021; McFarland et al., 2022), Paexo Shoulder (Maurice et al., 2020; Schmalz et al., 2019; Luque et al., 2020; Latella et al., 2022; Sierotowicz et al., 2022; Fritzsche et al., 2021, 2022), and Mate (Pacifico et al., 2022; Pinho et al., 2020), all of which showed measurable reductions in muscle activity or perceived exertion. Passive exoskeletons function without external power, instead storing and releasing mechanical energy as needed. This dominance likely reflects industry priorities, as passive designs offer operational efficiency, reliability, and ease of use in real-world settings. Supporting this, most field evaluations have focused on passive upper-limb exoskeletons (Pacifico et al., 2022; Spada et al., 2017; Hefferle et al., 2021; Bennett and Han, 2023), suggesting their current superiority for industrial applications.

Historically, exoskeleton development emphasized active systems (Dollar and Herr, 2008), particularly following successes in medical rehabilitation. A notable example is the Lokomat exoskeleton (Colombo et al., 2000), developed in 1994 for gait rehabilitation. The initial appeal of active systems stemmed from their capacity for tailored

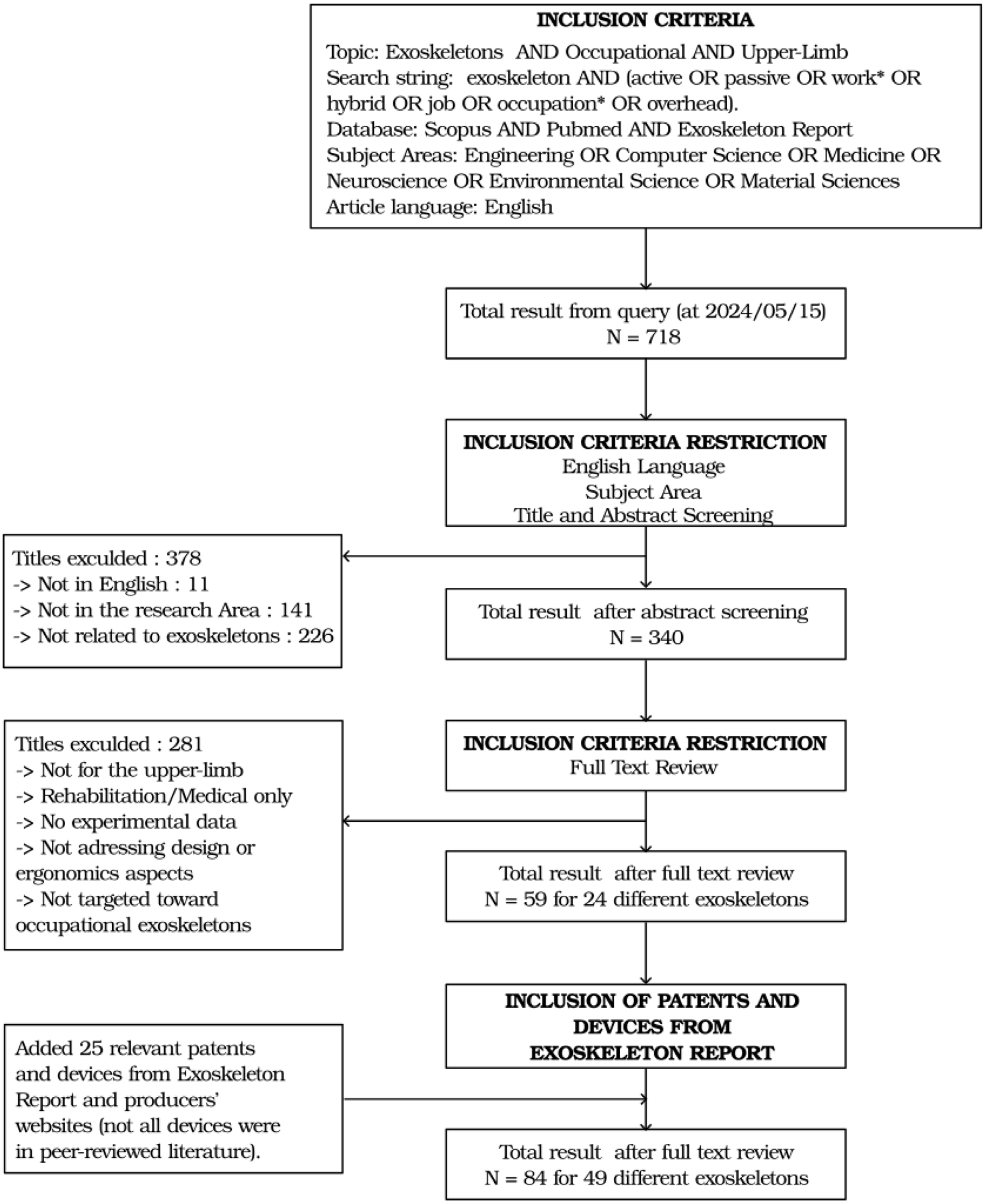

Fig. 3. Flowchart of the method used to include articles in the review.

assistance and energy injection, properties that seemed transferable to industrial tasks like repetitive overhead work. However, practical implementation revealed significant limitations: active exoskeletons introduce maintenance burdens, safety risks, design complexity, and weight penalties, while requiring continuous power (Villarroya López et al., 2023). These challenges have driven the shift toward passive designs (Jarrasse, 2019), which better align with industrial needs.

4.1.2. Anthropomorphism predominance

A significant proportion of industrial exoskeletons employ anthropomorphic designs that closely replicate human arm biomechanics (Fig. 6). This design paradigm strategically aligns the exoskeleton's rotational axes with the user's anatomical joint centers, thereby preserving natural kinematic chains (Herr, 2009). Such biomechanical congruence serves multiple critical functions: it enhances user comfort by distributing mechanical loads according to natural movement patterns, maintains the user's native task space, and prevents disruptions in inter-joint coordination. Studies comparing anthropomorphic and non-anthropomorphic structures support this: for example, the Exhauss Reliever (Desbrosses et al., 2021) induced back strain despite shoulder relief, while Skelex 360 (De Vries et al., 2021; Moyon et al., 2018; Ferreira et al., 2020; Ebrahimi, 2017) was reported to reduce perceived exertion but showed variability depending on task.

Table 2
Detailed technical specifications of upper-limb occupational exoskeletons used in industrial applications, including power source, kinematic structure, attachment ports, supported body parts, primary tasks, weight, and peak torque. *NA = Nat Addressed.

Device name (Company/Team)	Power source	Kinematics structure	Attachment port	Supported body part	Main task	Weight	Peak torque/Torque
Agadexo Shoulder (AGADE SR)	Hybrid	Rigid, anthropomorphic	Upper-arms	Shoulders, Back	Pick and carry, Overhead works	6 kg	8 kg × arm
Airframe (LEVITATE TECH)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.27 kg	–
Ant-A1 (LUBAN EXO)	Active	Rigid, anthropomorphic	Upper-arms	Shoulders, Back	Heavy lifting	5.2 kg	30 N m
Armor-Man (TILTAMAX)	Passive	Rigid, non-anthropomorphic	Hands, Arms	Shoulders	Tool holding (Camera)	25 kg	–
Bes-Ultra (ULS ROBOTICS)	Active	Rigid, anthropomorphic	Upper-arms, legs	Shoulders, Back, Knees	Pick and carry, Overhead works	25 kg	–
Besk G (CYBER HUMAN)	Passive	Rigid, non-anthropomorphic	Upper-arms	Shoulders	Overhead works	3 kg	12 kg
Carry (Nassour et al.)	Active	Soft	Upper-arms, forearms, hands	Arms	Carrying	–	–
CDYS (CRIMSON DYNAMICS)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.6 kg	–
DeltaSuit (AUXIVO)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	1.8 kg	6.6 N m
Enforcer (EXOMED)	Active	Fixed structure	Hands	Shoulders, Back	Tool holding	23.5 kg	120 kg
Ercura Arms (ERCURA)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2 kg	16 N m
Evo (EKSO BIONICS)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Tool holding, Overhead works	3.4 kg	6.8 N m
Exo Vest (EKSO BIONICS)	Passive	Rigid, anthropomorphic	Upper-arms, forearms	Shoulders	Overhead works	4.3 kg	–
Exo-01 (HILTI)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2 kg	–
Exo-S (HILTI)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.3 kg	–
Exhauss (lifter) (EXHAUSS)	Passive	Rigid, non-anthropomorphic	Hands	Arms	Heavy lifting	5.8 kg	25 kg
Exhauss (worker) (EXHAUSS)	Passive	Rigid, non-anthropomorphic	Hands	Shoulders, Arms	Repetitive tasks	8.9 kg	25 kg
Exhauss (reliever) (EXHAUSS)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	7.9 kg	25 kg
Exy One (EXY)	Passive	Rigid, non-anthropomorphic	Upper-arms	Shoulders	Overhead works	3.55 kg	8 kg × arm
Fawcett Exovest (THE TIFFEN COMPANY)	Passive	Rigid, non-anthropomorphic	Hands	Shoulders, Arms	Tool holding (Camera)	4.85 kg	–
Fortis (LOCKHEED MARTIN)	Passive	Fixed structure	Hands	Shoulders, Back	Tool holding	–	23 kg
Hapo Front (ERGOSANTE')	Passive	Soft	Upper-arms, forearms	Shoulders	Repetitive tasks, Arms extended	1.3 kg	6 kg
Hapo Up (ERGOSANTE')	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	1.67 kg	3.8 kg × arm
Holdupper (EXOMED)	Passive	Rigid, anthropomorphic	Elbow, forearms	Shoulders	Overhead works	4.8 kg	8 kg × arm
Hust-Ev (Du et al.)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	1.3 kg	–
H-pulse (IUVO)	Hybrid	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	5 kg	6 N m
H-Vex (HYUNDAI)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.5 kg	5.5 kg
Light (HTM)	Passive	Rigid, anthropomorphic	Upper-arms, forearms	Arms	Tool Handling	2.9 kg	6 kg
MAPS_E (ULS ROBOTICS)	Active	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	6.5 kg	20 kg
Mate (COMAU (IUVO))	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	4 kg	5.46 kg × arm
Mate-XT (COMAU (IUVO))	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	3 kg	5.5 kg × arm
MuscleSuit (INNOPHYS)	Active	Rigid, non-anthropomorphic	Hands	Shoulders, Back	Heavy lifting, Pick and carry	8.1 kg	35.7 Kg, 140 N m
Lucy 2.0 (PROJECT SMARTASSIST)	Active	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	–	–
Ottobock Shoulder (OTTOBOCK)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	–	–

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Table 2 (*continued*).

Paexo Shoulder (OTTOBOCK)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	1.9 kg	11.7 N
OmniSuit (AUXIVO)	Passive	Rigid, anthropomorphic	Upper-arms, legs	Shoulders, Back	Overhead works, Heavy lifting	2.7 kg	–
Plum' (HTM)	Passive	Rigid, anthropomorphic	Upper-arms	Arms	Overhead works	1.5 kg	6 kg
Robo-Mate (passive) (EUROPEAN PROJECT)	Passive	Rigid, non-anthropomorphic	Arms	Shoulders, Arms	Medium/heavy loads handling	3.7 kg	7.5 kg × arm
Robo-Mate (active) (EUROPEAN PROJECT)	Active	Rigid, non-anthropomorphic	Arms	Shoulders, Arms	Pick and place tasks	2.3 kg	7.5 kg × arm
S700 (EXOIQ)	Active	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	6.5 kg	5 kg
Shiva Exo (ERGOSANTE')	Passive	Rigid, anthropomorphic	Upper-arms, forearms, thighs	Shoulders, Back	Pick and carry, Overhead works	6.85 kg	7.5 kg × arm
ShoulderX (SUITX)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	3.2 kg	5.4 kg
Skelex 360 (SKELEX)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.3 kg	4 kg
Stuttgart exo jacket (FRAUNHOFER INSTITUTE)	Active	Rigid, anthropomorphic	Upper-arms, forearms	Shoulders, Arms	Overhead works	–	40 N m
Task AR 3.0 (DAYDO CO., LTD)	Passive	Rigid, anthropomorphic	Upper-arms, neck	Shoulders, Neck	Overhead works	1.7 kg	3.0 kg
Titan Arms PUCE4 (HYETONE EXOSKELETON)	Passive	Rigid, anthropomorphic	Upper-arms	Shoulders	Overhead works	2.8 kg	7 kg
Uplift (MAWASHI)	Passive	Rigid, anthropomorphic	Upper-arms, forearms, legs	Shoulders, Back, Knees	Pick and carry, Overhead works	–	–
X-Arm (EXORISE)	Passive	Fixed structure	Hands	Shoulders, Back	Tool holding	17 kg	40 kg
X-Rise (EXORISE)	Passive	Rigid, non-anthropomorphic	Upper-arms	Shoulders	Overhead works	2-3 kg	6 kg

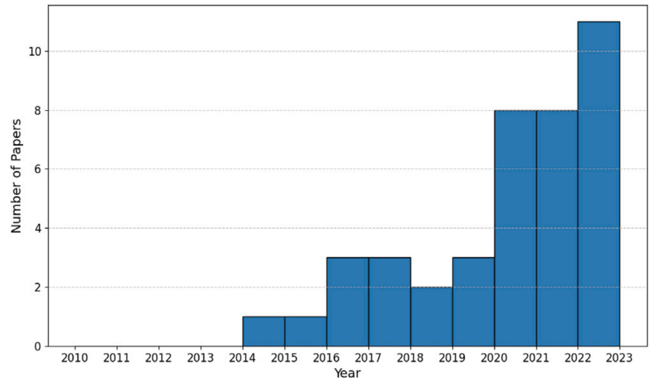

Fig. 4. Number of publications per year.

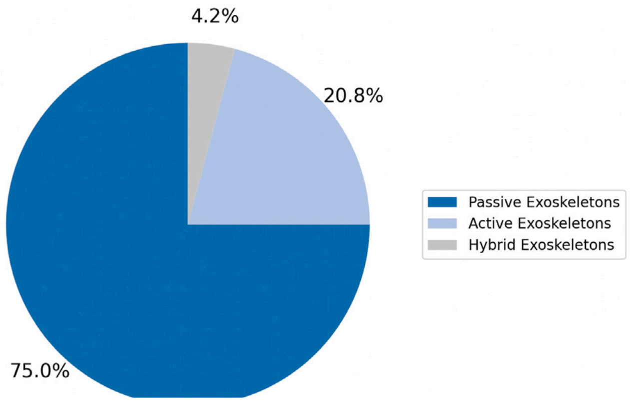

Fig. 5. Actuation technology based distribution.

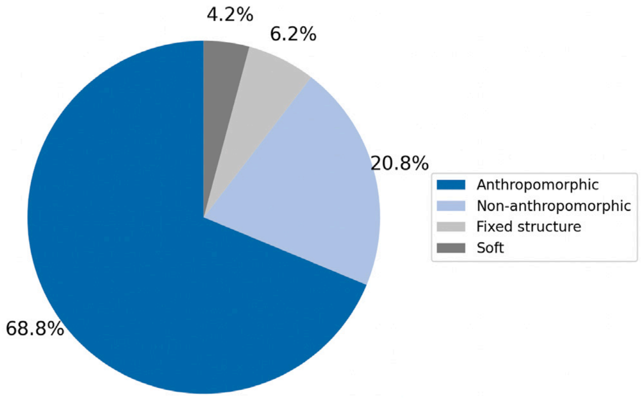

Fig. 6. Kinematics structure based distribution.

Complementing this anthropomorphic approach is a clear design trend toward minimizing the number of attachment points to the body. Recent exoskeletons typically interface with users at only essential anatomical locations, a strategy that yields three primary benefits: (1) reduced soft-tissue discomfort and thermal accumulation, (2) diminished risk of inducing unnatural movement patterns, and (3) preserved biomechanical integrity of unsupported body segments. This minimal-contact philosophy is particularly advantageous in industrial environments where workers must transition between diverse tasks requiring varied postures and movement patterns.

However, the convergence of these two design principles, anthropomorphic kinematics and minimal attachment points, has led to a notable specialization in joint-specific support. Analysis of current industrial exoskeletons reveals a predominance of single-joint assistance

Table 3
Overview of studies conducted on the effect of upper-limb occupational exoskeletons, focusing on the aspects analyzed, such as muscle activity, side effects, after-effects, and long-term evaluations. This table outlines which specific areas have been studied for each device, including evaluations of unsupported body parts, and whether long-term effects were considered. (Abbreviations: UA = User Acceptance; IU = Intention of Use; VAS = Visual Analog Scale; RPE = Rate of Perceived Effort; RPD = Rate of Perceived Discomfort; TSI = Tissue Saturation Index; MAF = Maximum Acceptable Frequency; FMG = Force MyoGraphy; LPE = Local Perceived Exertion; TAM = Technology Acceptance Model).

Device name (Company/Team)	Publications	Main measurement	Complementary measurement	Residual effects	Long-term effects	Not supported body area
Agadexo Shoulder (AGADE SR)	–	–	–	–	–	–
Airframe (LEVITATE TECH)	Kong et al. (2023), Gillette et al. (2022), Groos et al. (2022), Masood et al. (2022), Schwerha et al. (2021), Iranzo et al. (2020), Rubenstone (2019), Spada et al. (2017), Weston et al. (2021) and McFarland et al. (2022)	Muscles activity via EMG (Kong et al., 2023; Gillette et al., 2022; Groos et al., 2022; Iranzo et al., 2020), Muscles activity via TSI (Weston et al., 2021), Kinematics via MoCap (Iranzo et al., 2020; McFarland et al., 2022)	Subjective perception (RPD) (Kong et al., 2023; Gillette et al., 2022; Schwerha et al., 2021; Weston et al., 2021); Heart rate (Groos et al., 2022), Task time, Task precision (Spada et al., 2017; McFarland et al., 2022)	–	–	Lower Limbs (Kong et al., 2023), Back (Kong et al., 2023; Gillette et al., 2022; Iranzo et al., 2020; Weston et al., 2021)
Ant-A1 (LUBAN EXO)	–	–	–	–	–	–
Armor-Man (TILTAMAX)	–	–	–	–	–	–
Bes-Ultra (ULS ROBOTICS)	–	–	–	–	–	–
Besk G (CYBER HUMAN)	–	–	–	–	–	–
Carry (Nassour et al.)	Nassour et al. (2021)	Muscles activity via EMG	Oxygen consumption	–	–	–
CDYS (CRIMSON DYNAMICS)	Hefferle et al. (2021)	–	Subjective perception (RPE, VAS)	–	–	–
DeltaSuit (AUXIVO)	Brunner et al. (2023)	Muscles activity via EMG	Subjective perceptions (RPD, RPE), Heart rate	–	–	–
Enforcer (EXOMED)	–	–	–	–	–	–
Ercura Arms (ERCURA)	–	–	–	–	–	–
Evo (EKSO BIONICS)	Bennett and Han (2023) and Raveendranath et al. (2024)	Kinematics via IMU (Bennett and Han, 2023)	Heart rate, Task time (Bennett and Han, 2023), Task precision (Raveendranath et al., 2024)	–	–	–
Exo Vest (EKSO BIONICS)	Luque et al. (2020), Weston et al. (2021), Smets (2019), Kim et al. (2021) and Daratany and Taveira (2020)	Muscles activity via TSI (Weston et al., 2021), Kinematics via IMU (Luque et al., 2020)	Subjective perception (RPD) (Weston et al., 2021), Heart rate (Daratany and Taveira, 2020)	–	Subjective perception (Smets, 2019; Kim et al., 2021)	Back (Weston et al., 2021)
Exo-01 (HILTI)	Bennett and Han (2023)	Kinematics via IMU	Heart rate, Task time	–	–	–
Exo-S (HILTI)	–	–	–	–	–	–
Exhauss (lifter) (EXHAUSS)	–	–	–	–	–	–
Exhauss (worker) (EXHAUSS)	Theurel et al. (2017)	Muscles activity via EMG, Kinematics via IMU	Postural balance, Heart rate, Subjective perception (RPE), Task time	–	–	Lower limb
Exhauss (reliever) (EXHAUSS)	Desbrosses et al. (2021)	Muscles activity via EMG	Postural balance	–	–	Back
Exy One (EXY)	–	–	–	–	–	–
Fawcett Exovest (THE TIFFEN COMPANY)	Alabdulkarim and Nussbaum (2019) and Rashedi et al. (2014)	Muscles activity via EMG (Alabdulkarim and Nussbaum, 2019; Rashedi et al., 2014)	Subjective perception (MAF, RPD) (Alabdulkarim and Nussbaum, 2019; Rashedi et al., 2014)	–	–	Back (Alabdulkarim and Nussbaum, 2019; Rashedi et al., 2014)
Fortis (LOCKHEED MARTIN)	Alabdulkarim and Nussbaum (2019)	Muscles activity via EMG	Subjective perception (MAF, RPD)	–	–	Back
Hapo Front (ERGOSANTE')	Tellier et al. (2021)	Muscles activity via EMG	Subjective perception (RPE, RPD), Postural balance	–	–	–

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Table 3 (*continued*).

Hapo Up (ERGOSANTE')	–	–	–	–	–	–
Holdupper (EXOMED)	–	–	–	–	–	–
Hust-Ev (Du et al.)	Du et al. (2022)	Muscles activity via EMG, Kinematics via MoCap	Task precision	–	–	Lower Limbs, Back
H-pulse (IUVO)	Grazi et al. (2020)	Muscles activity via EMG	Subjective perceptions (NASA, RPE), Heart rate	–	–	–
H-Vex (HYUNDAI)	Kong et al. (2023)	Muscles activity via EMG	Subjective perception (RPD)	–	–	Lower Limbs, Back
Light (HTM)	–	–	–	–	–	–
Maps_E (ULS ROBOTICS)	–	–	–	–	–	–
Mate (COMAU (IUVO))	Luque et al. (2020), Liu et al. (2023), Pacifico et al. (2022) and Pinho et al. (2020)	Muscles activity via EMG (Pinho et al., 2020; Pacifico et al., 2022), Kinematics via IMU (Luque et al., 2020)	Subjective perceptions (LPE) (Pacifico et al., 2022), Limb vibration (Pinho et al., 2020)	–	–	–
Mate-XT (COMAU (IUVO))	Ramella et al. (2024)	Muscles activity via EMG, Kinematics via IMU	–	–	–	–
MuscleSuit (INNOPHYS)	–	–	–	–	–	–
Lucy 2.0 (PROJECT SMARTASSIST)	Otten et al. (2018)	Muscles activity via EMG	Subjective perception (RPE)	–	–	–
Ottobock Shoulder (OTTOBOCK)	–	–	–	–	–	–
Paexo Shoulder (OTTOBOCK)	Latella et al. (2022), Sierotowicz et al. (2022), Fritzsche et al. (2021, 2022), Pinho et al. (2020), Maurice et al. (2020), Schmalz et al. (2019) and Luque et al. (2020)	Muscles activity via EMG (Sierotowicz et al., 2022; Maurice et al., 2020; Pinho et al., 2020; Schmalz et al., 2019), Muscles activity via FMG (Sierotowicz et al., 2022), Kinematics via IMU (Latella et al., 2022; Maurice et al., 2020; Luque et al., 2020), Joint forces via Simulation (Fritzsche et al., 2021, 2022)	Subjective perceptions (RPE, RPD) (Maurice et al., 2020), Ground Reaction (Latella et al., 2022; Maurice et al., 2020), Heart rate, Oxygen consumption (Maurice et al., 2020; Schmalz et al., 2019)	–	–	Back (Fritzsche et al., 2021, 2022; Schmalz et al., 2019), Abdomen (Schmalz et al., 2019), Whole body kinematics (Latella et al., 2022; Maurice et al., 2020)
OmniSuit (AUXIVO)	van Sluijs et al. (2024)	–	–	–	–	–
Plum' (HTM)	–	–	–	–	–	–
Robo-Mate (passive) (EUROPEAN PROJECT)	Altenburger et al. (2016), De Looze et al. (2016), Stadler et al. (2014), van der Vorm et al. (2015), Stadler et al. (2016) and Huysamen et al. (2018)	Muscles activity via EMG (Huysamen et al., 2018)	Subjective perception (RPE) (Huysamen et al., 2018)	–	–	–
Robo-Mate (active) (EUROPEAN PROJECT)	–	–	–	–	–	–
S700 (EXOIQ)	–	–	–	–	–	–
Shiva Exo (ERGOSANTE')	–	–	–	–	–	–
ShoulderX (SUITX)	Weston et al. (2021), Alabdulkarim and Nussbaum (2019), Engelhoven et al. (2018) and Pinho et al. (2020)	Muscles activity via EMG (Alabdulkarim and Nussbaum, 2019; Engelhoven et al., 2018; Pinho et al., 2020), Muscles activity via TSI (Weston et al., 2021)	Subjective perception (RPD) (Weston et al., 2021), Subjective perceptions (MAF, RPD) (Alabdulkarim and Nussbaum, 2019), Limb vibration (Pinho et al., 2020)	–	–	Back (Weston et al., 2021; Alabdulkarim and Nussbaum, 2019)

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Table 3 (*continued*).

Skelex 360 (SKELEX)	De Vries et al. (2021), Moyon et al. (2018), Ferreira et al. (2020) and Hefferle et al. (2021)	Muscles activity via EMG (De Vries et al., 2021)	Subjective perception (RPE, RPD) (De Vries et al., 2021); Heart rate, Subjective perceptions (RPE) (Moyon et al., 2018), Subjective perceptions (RPE, VAS) (Hefferle et al., 2021), Subjective perceptions (UA, IU) (Ferreira et al., 2020)	–	–	–
Stuttgart exo jacket (FRAUNHOFER INSTITUTE)	Ebrahimi (2017)	Kinematics via MoCap	–	–	–	Whole body kinematics
Task AR 3.0 (DAYDO CO., LTD)	–	–	–	–	–	–
Titan Arms PUCE4 (HYETONE EXOSKELETON)	–	–	–	–	–	–
Uplift (MAWASHI)	–	–	–	–	–	–
X-Arm (EXORISE)	–	–	–	–	–	–
X-Rise (EXORISE)	–	–	–	–	–	–

systems, with particular emphasis on shoulder joint support (as evidenced by upper-arm attachment predominance in Table 2). While this focused approach simplifies mechanical design and control requirements, it introduces potential ergonomic trade-offs. The selective support of individual joints may create functional asymmetries in multi-articular tasks, where unsupported joints must compensate for the assisted motion.

4.1.3. Supported body area

Most exoskeletons are designed to be attached to the upper arms, providing stable support for the shoulders during overhead tasks and repetitive motions without significantly limiting mobility. This attachment point is effective for general support, but may lack the precision needed for tasks requiring fine motor control which most of the case is done with the elbow, and then the wrist following the natural proximal-to-distal sequence of the upper-limb motion (Serrien and Baeyens, 2017). To address this, some exoskeletons extend their support to the forearms, such as the Holdupper and ShoulderX, which provide additional stability for tasks requiring extended arm positioning or precision, especially when using tools. However, while this dual support enhances stability, it can sometimes restrict natural arm movement, which may be a limitation for tasks requiring a high degree of flexibility and Range Of Motion (ROM). This trade-off between support and mobility must be carefully considered when selecting or designing exoskeletons for specific industrial applications. For tasks involving direct manipulation of tools or objects, endpoint-based exoskeletons also sometimes named supernumerary limbs (SNL), are particularly used. These devices attach directly to the tool or object being handled, reducing strain on smaller joints and muscles, such as those in the hands and wrists. This design is exemplified by the Armor Man exoskeleton, which is used for tasks like camera holding in filming. However, due to their weight, that is generally heavier (see Fig. 8), and to the asymmetry they are generating, field evaluations of devices show to overall increase muscle activity (De Vries and Looze, 2019) with, for example, devices like the Fawcett Exovest (Rashedi et al., 2014), Fortis (Alabdulkarim and Nussbaum, 2019) which demonstrated that endpoint-based support can increase muscular load in the back and reduce usability in dynamic tasks.

Full-body exoskeletons, which provide support to the shoulders, back, and legs, are rare in industrial contexts but offer comprehensive assistance for tasks that involve a wide range of motion. For example the Uplift or the Bes-Ultra exoskeletons were designed both to pick, carry and overhead work. The Omnisuit by AUXIVO (van Sluijs et al., 2024) is also one example, designed to reduce workload and fatigue across the shoulder and the back regions. This modularity in the supported tasks and goals enhances the versatility of exoskeleton systems, making them adaptable to various industrial needs while maintaining targeted support.

4.1.4. Main tasks

Overhead work remains the most common application for industrial exoskeletons, with devices like the Airframe (Kong et al., 2023; Groos et al., 2022), Paexo Shoulder (Schmalz et al., 2019), and Mate-XT (Weston et al., 2021; Alabdulkarim and Nussbaum, 2019; Engelhoven et al., 2018) specifically designed to reduce shoulder strain during repetitive tasks. These exoskeletons are often lightweight and passive, which is advantageous for prolonged use as they do not add significant weight to the user. Evidence from studies on those devices consistently shows reduced deltoid activation during overhead tasks, but at the cost of restricted ROM or compensatory effort in other muscles.

For tasks involving heavier loads, such as tool holding, exoskeletons like the Enforcer and X-Arm use active or fixed structures to provide robust support. However, these designs come with a trade-off, as the increased support often results in reduced flexibility and greater weight. This highlights the ongoing challenge of balancing support with mobility, particularly in tasks that require a blend of strength and precision. Devices designed for heavy lifting, like the Fortis and Muscle Upper, often utilize both passive and active systems to manage substantial weights while minimizing user strain. These exoskeletons must be carefully designed to ensure they meet the specific demands of their intended tasks without introducing new ergonomic challenges.

The mass of the tool or object being handled can significantly influence the effectiveness of an exoskeleton, as reported in various studies (Rashedi et al., 2014; Huysamen et al., 2018; Kim et al., 2018). This consideration is critical when designing or selecting exoskeletons for specific industrial applications, as the device must be capable of accommodating the varying weights and dynamics of the tools used.

4.1.5. Variability in weight and torque capability

There is a wide range of weight and torque capacities among industrial exoskeletons, from around 3 to 40 kg, reflecting the diversity of tasks they are designed to support (Fig. 7). Exoskeletons intended for heavy lifting typically have higher torque capacities but may also be heavier, which can affect user fatigue and overall comfort. Conversely, exoskeletons designed for overhead work prioritize lightweight designs to minimize user fatigue, often at the expense of torque capacity.

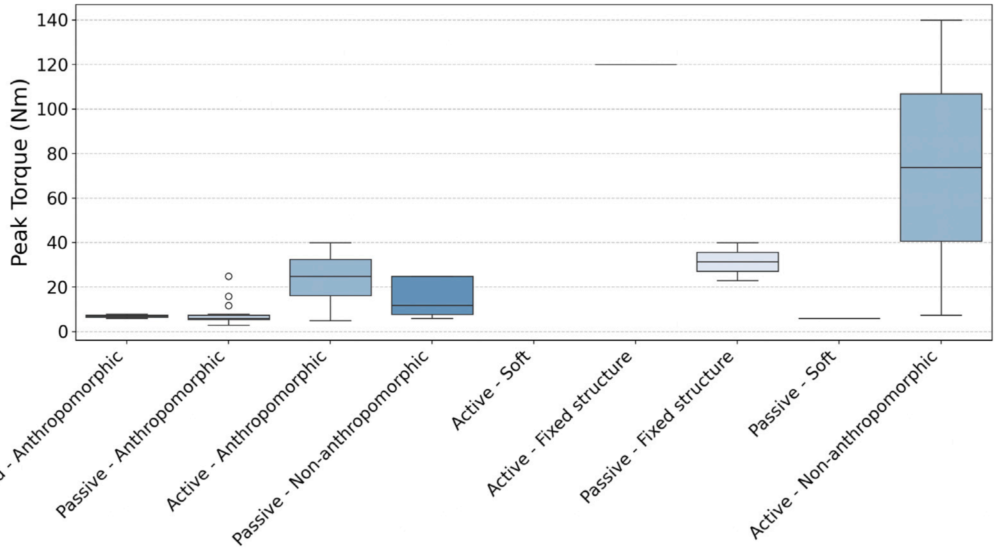

Fig. 7. Distribution of Peak Torque in different devices.

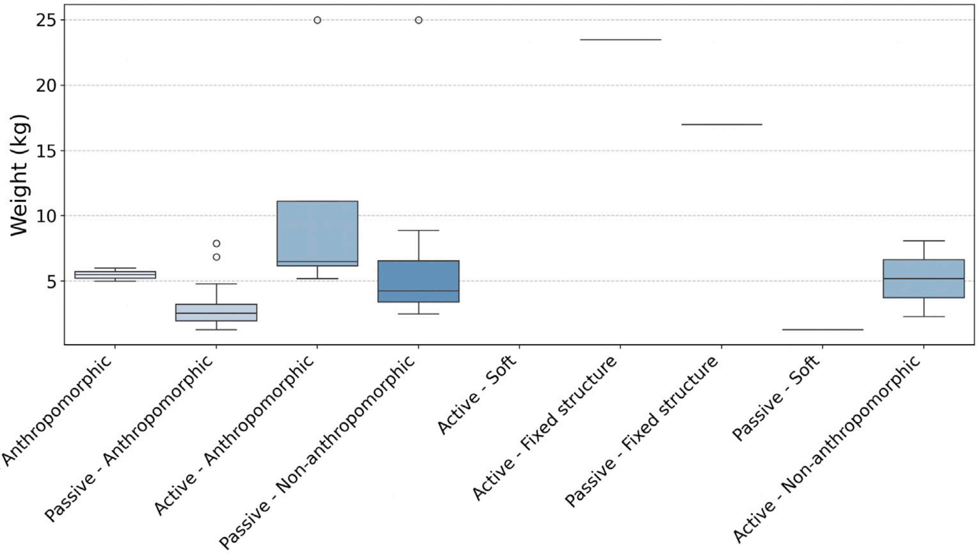

Fig. 8. Distribution of Weight in different devices.

This variability underscores the importance of selecting exoskeletons based on the specific requirements of the task and the working environment. Passive exoskeletons, in particular, tend to prioritize lightweight construction to enhance usability and reduce fatigue, while active exoskeletons are more performance-oriented, offering higher torque capacities at the cost of increased weight and complexity (Fig. 8). This trade-off must be carefully managed to ensure that the exoskeleton provides the necessary support without compromising the user's ability to perform their tasks effectively. For instance, Kim et al. (2018) found that tool mass strongly influenced the benefits of passive vests, while Alabdulkarim and Nussbaum (2019) demonstrated that heavier devices such as the Fawcett Exovest reduced performance under drilling tasks.

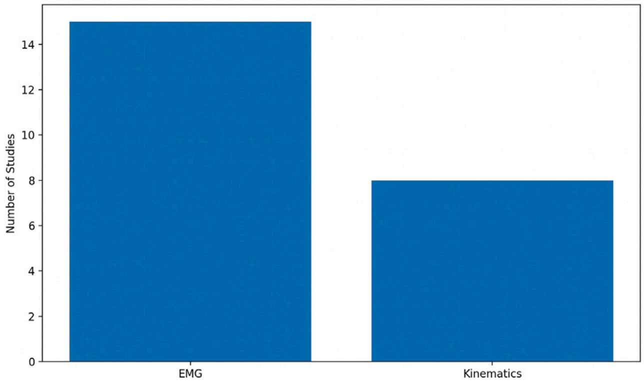

Fig. 9. Distribution of main measurements in exoskeleton studies.

4.2. Experimental evaluation

In these paragraphs, the results obtained from Table 3 will be discussed.

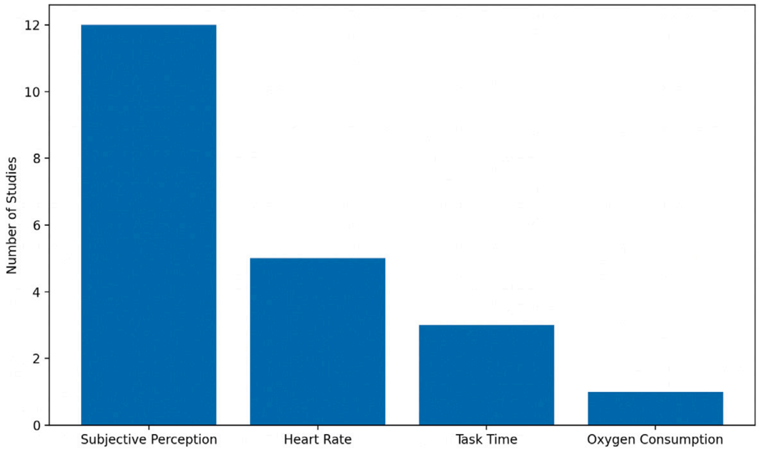

Fig. 10. Distribution of complementary measurements in exoskeleton studies.

4.2.1. Principal measurements: EMG and kinematics

Most studies on industrial exoskeletons evaluate their effect using muscles activity measured via Electromyography (EMG) (Fig. 9). As exoskeletons are usually used with the aim of reducing fatigue, EMG is typically used to evaluate the decrease in the activity of key muscles involved in shoulder, arm, and upper body movements (Airframe (Kong et al., 2023; Gillette et al., 2022; Groos et al., 2022; Iranzo et al., 2020), Carry (Nassour et al., 2021), DeltaSuit (Brunner et al., 2023), ExoVest (Weston et al., 2021), Exhauss (Theurel et al., 2017; Desbrosses et al., 2021), Fawcette Exovest (Alabdulkarim and Nussbaum, 2019; Rashedi et al., 2014), Fortis (Alabdulkarim et al., 2019), Happ Front (Tellier et al., 2021), Hust-Ev (Du et al., 2022) ect.), such as the Anterior and Medial Deltoid, Posterior Deltoid, Upper Trapezius, Latissimus Dorsi, Erector Spinae, Pectoralis Major, Biceps Brachii, and Triceps Brachii (Kim et al., 2022). This measurement is critical for understanding how exoskeletons reduce muscle strain during physically demanding tasks. For example, studies on devices such as the Paexo Shoulder and the Mate (Comau) exoskeletons have used EMG to demonstrate significant reductions in muscle activity during overhead work (Maurice et al., 2020; Pacifico et al., 2022). Similarly, the Airframe (Kong et al., 2023; Gillette et al., 2022; Groos et al., 2022) and Skelex 360 (De Vries et al., 2021; Moyon et al., 2018) have repeatedly shown deltoid and trapezius relief, while Hust-Ev (Du et al., 2022) provided EMG evidence of improved endurance in overhead precision tasks. However, focusing solely on EMG without considering other aspects may limit the understanding of an exoskeleton's overall impact.

In addition to EMG, many studies complement their evaluations with kinematic measurements, such as Range of Motion (ROM) (Luque et al., 2020; Maurice et al., 2020), joint angle trajectories (Ebrahimi, 2017), and the speed of body segments. These parameters help to understand how exoskeletons influence movement and motor control during use. For instance, research on the Paexo Shoulder and Mate XT exoskeletons has shown some restriction in ROM, particularly in extreme postures like shoulder abduction and elbow flexion (Schmalz et al., 2019; Luque et al., 2020).

4.2.2. Complementary measurement: Heart rate, and subjective metrics

Subjective parameters, including Ratings of Perceived Exertion (RPE) and Ratings of Perceived Discomfort (RPD), are also vital to understanding user experience. These metrics provide insights into comfort and ease of use, critical factors for adoption in industrial settings (Moeller et al., 2022). Devices like the Airframe and Exo Vest have been evaluated using both RPE and RPD to assess how the user perceives the exertion and discomfort during tasks (Kong et al., 2023; Gillette et al., 2022).

Other measurements include heart rate (Groos et al., 2022; Brunner et al., 2023; Grazi et al., 2020), energy expenditure (Maurice et al., 2020; Schmalz et al., 2019; Nassour et al., 2021), and task performance metrics such as time taken to complete tasks (Maurice et al., 2020; Theurel et al., 2017) or postural balance (Theurel et al., 2017) (Fig. 10), which give a broader perspective on the physiological effects of exoskeleton use (Spada et al., 2017; Weston et al., 2021).

4.2.3. Residual and long-term effects

Despite the numerous metrics used to evaluate exoskeletons effect while the user wears it, a critical gap remains : long-term effects and residual effects of exoskeleton use are still under-researched. Most studies, such as those on the Paexo Shoulder, focus on short-term use. However, it has been shown that exoskeletons can still alter motor control even once removes (Proietti et al., 2017). Moreover, current studies only evaluate the impact of the devices on directly supported body areas, like the muscles of the shoulder and the arm. However, residual effects such as changes in posture or movement habits (Theurel et al., 2018) that could persist after removing the exoskeleton are rarely considered, even though they are critical for understanding the prolonged impact of these devices (Fritzsche et al., 2021, 2022). In this review, apart from Smets (2019) and Kim et al. (2021) who conducted studies over respectively 1 year and 18 months, no other studies have worked on long term impact of exoskeletons. However, these two studies focuses on qualitative questionnaires, lacking some quantitative metrics to fully assess exoskeletons' impact.

Research is needed to assess whether exoskeletons could inadvertently cause long-term musculoskeletal issues due to compensatory movements or altered motor control. Flor-Unda et al. (2025) emphasized that such long-term and residual effects are rarely studied systematically, and Moeller et al. (2022) highlighted the lack of transferability from laboratory to field. For example, Engelhoven et al. (2018) observed increased activation in the Triceps Brachii during overhead work, suggesting a redistribution of muscular effort, which could pose risks for other muscle groups in the long run.

4.2.4. Effect on unsupported body areas

Finally, a major missing topic in exoskeleton research is the indirect effect of those on unsupported body areas. This review analyzed 49 exoskeletons, yet only 11 were assessed for effects beyond the directly supported area (primarily the shoulder). Of these 11, nine focused solely on the back—a region adjacent to the supported area. Just two exoskeletons were evaluated for their impact on whole-body kinematics while worn: the Stuttgart Exo-Jacket (Ebrahimi, 2017) and the Paexo Shoulder (Latella et al., 2022; Maurice et al., 2020). Nevertheless, this topic is critical as, for example, studies on the Paexo Shoulder and

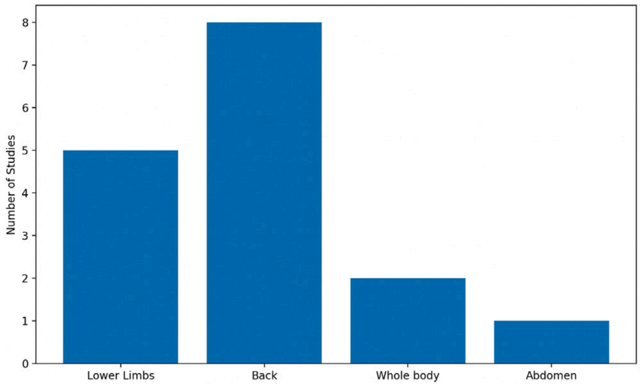

Fig. 11. Distribution of unsupported body areas considered in exoskeleton studies.

Airframe showed that while these devices offload shoulder muscles, they provide little to no support for the lower back or legs, potentially leading to overuse or strain in these areas during extended use (Schmalz et al., 2019; Kong et al., 2023). The Exhauss Reliever (Desbrosses et al., 2021) and Fawcett Exovest (Alabdulkarim and Nussbaum, 2019; Rashedi et al., 2014) similarly increased load transfer to the back, underscoring the risk of secondary strain. This limitation is significant, as prolonged compensatory movement patterns could result in discomfort or injury in unsupported areas (see Fig. 11).

5. Limitations and future scope

Despite advancements in design, particularly in aligning exoskeletons with natural biomechanics, significant research gaps remain. One of the most striking omissions in current studies is the evaluation of post-effects of exoskeleton use, such as residual impacts that persist after the device is removed. This aspect has been largely overlooked, despite its importance in understanding long-term safety and ensuring that exoskeletons do not introduce new risks with prolonged use.

Additionally, much of the existing research has been conducted in controlled laboratory settings, which fail to fully capture the complexity of real-world industrial environments. Factors such as task variability, work transitions, and long-duration usage significantly influence device effectiveness but are underexplored. Addressing these limitations requires long-term field studies, particularly for active exoskeletons, to assess their performance in dynamic work scenarios and across diverse industrial sectors.

Looking ahead, future research should also explore the integration of intelligent control strategies, such as adaptive or AI-driven assistance, to improve user-device interaction and reduce cognitive load. Advances in lightweight materials, wearable sensing, and personalized fitting strategies could further enhance usability and worker acceptance. Finally, the development of regulatory standards and unified evaluation frameworks at both national and international levels will be critical to ensuring safe, consistent, and sustainable adoption of exoskeletons across industries worldwide.

6. Conclusion

The development of occupational exoskeletons, particularly upper-limb devices, shows considerable potential for reducing work-related musculoskeletal disorders (MSDs) across industries. However, evaluating these devices must go beyond immediate reductions in muscle activity, as such outcomes provide only a partial picture of efficacy. Distinct technological approaches – passive, active, or hybrid – offer different advantages and limitations, underscoring the importance of matching device design to specific tasks and environments.

A key takeaway is the current dominance of passive exoskeletons in industrial applications due to their simplicity and reliability, whereas active systems face challenges in real-world deployment. Ensuring safe, effective, and sustainable integration of exoskeletons into industrial practice will require not only technical refinement but also comprehensive evaluation strategies that account for both user experience and long-term occupational outcomes.

CRediT authorship contribution statement

Giovanni Brunelli: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Océane Dubois:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Monica Tiboni:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Nathanaël Jarrassé:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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