State-of-the-Art Review of Wearable Exoskeletons

Rehabilitation, Personal Mobility, and Industrial Applications

IRISH MANUFACTURING RESEARCH

DCU
Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

Insight
RESEARCH IRELAND CENTRE FOR DATA ANALYTICS

Index

1. Abstract

Wearable exoskeletons are moving from research prototypes to practical systems used in clinics, communities, and workplaces. This report reviews the state of the art across three application domains: rehabilitation exoskeletons used to deliver gait training, personal mobility exoskeletons intended to support everyday walking and community barriers, and industrial exoskeletons designed to reduce physical demands during work tasks. For each domain, the report describes user needs and use-cases, current system approaches (mechanics, actuation, sensing, control, safety, and usability), evidence from clinical and operational validation, and the main technology gaps and opportunities.

In rehabilitation, published evidence is dominated by treadmill-based and overground lower-limb systems evaluated with standard mobility and independence outcomes. Many studies report improvements for selected users, but comparisons across devices remain difficult because protocols, training dose, and outcome selection vary widely and follow-up data are limited. Current clinical systems often prioritise robust, therapist-operable control strategies, while more adaptive, intent-aware approaches are being developed but are not yet consistently validated in routine practice.

In personal mobility, evidence spans three main areas: community-delivered programmes in older adults, rigid devices designed to support high-demand tasks such as stairs and transfers, and lightweight passive or quasi-passive devices that reduce effort during walking or running. Structured community studies report feasibility and functional improvements, while controlled laboratory evaluations commonly report reduced metabolic cost under controlled conditions. However, long-term daily use remains constrained by worn mass and where that mass sits on the body, durability, the need for user adaptation and training, and acceptance factors such as comfort, appearance, and fit with daily routines and existing mobility aids.

In industry, the literature focuses toward passive shoulder and back supports evaluated over short durations. Studies often report reduced muscle activity or perceived exertion in targeted tasks, but results are more variable in dynamic workflows, and long-term prevention impact is still uncertain due to limited long-duration field data. Across domains, the report highlights shared development priorities: lighter and better-fitting systems, faster donning and doffing, safe performance during transitions and variable real-world conditions, practical fail-safe behaviour outside controlled environments, and longer evaluations that capture sustained use, safety, side effects, and meaningful real-world impact.

2. Introduction

Wearable exoskeletons are now a practical option for assisting human movement in three settings that have different goals and constraints: clinical rehabilitation, everyday community mobility, and industrial work. Across all three, the basic idea is the same: a wearable structure applies forces or torques through an interface (straps, cuffs, braces, boots, or textile attachments) to support a joint or body segment.[1] What changes across domains is the priority. Rehabilitation systems are judged by whether they help deliver safe, repeatable therapy and improve functional outcomes in clinical populations.[1] Personal mobility systems are judged by whether they are wearable enough for daily routines and provide clear benefit in real environments.[2] Industrial systems are judged by whether they reduce physical exposure without slowing work or creating new risks.[3]

2.1 Why exoskeletons matter in rehabilitation, mobility, and work

In rehabilitation, powered exoskeletons are used to deliver high-repetition gait practice and standing/stepping tasks for people with neurological injury or disease. Clinical reviews describe how treadmill-based systems and overground wearable devices are integrated into supervised programmes, especially for stroke and spinal cord injury, and how they are evaluated using standard tests and functional scales.[1] This domain is driven by service delivery realities: setup time, staffing, supervision, and safe operation under clinical workflows are as important as the mechanical performance of the device.[1]

In personal mobility, the goal shifts from therapy delivery to daily function. Studies include structured community programmes in older adults that use real environments (hallways, ramps, curbs, stairs, and multi-terrain walking), as well as controlled evaluations showing reduced metabolic cost for walking or running under tuned conditions.[2] This domain forces practical design questions that can be secondary in clinic-only systems. Because the user must wear the device in daily life, practical factors such as worn mass, where that mass sits on the body, comfort over long wear, and durability and maintenance demands, often determine whether the system is usable.[4]

In industry, the immediate objective is strain reduction during work tasks such as overhead reaching, manual handling, and sustained awkward postures. Reviews and meta-analyses report that many studies measure changes in muscle activity, posture/kinematics, and perceived exertion/discomfort, with a literature that is still dominated by short-duration trials

---

[1] Plaza et al., 2021. *Lower-limb medical and rehabilitation exoskeletons: A review of the current designs.* IEEE Reviews in Biomedical Engineering**,** 16, pp.278–291.
[2] Jayaraman et al., 2022. Modular hip exoskeleton improves walking function and reduces sedentary time in community-dwelling older adults. Journal of NeuroEngineering and Rehabilitation, 19(1), 144.
[3] Bär et al., 2021. The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton–A systematic review and meta-analysis. Applied Ergonomics, 94, 103385.
[4] Bougrinat et al., 2019. Design and development of a lightweight ankle exoskeleton for human walking augmentation. Mechatronics, 64, 102297.

and passive devices.[5] A consistent discussion is the gap between laboratory results and real workplace performance. Field studies are harder to run, often smaller, and must account for workflow variability, comfort across a shift, compatibility with PPE, and organisational implementation factors such as training, maintenance, and voluntary use.[6]

2.2 Technology landscape

Across domains, exoskeleton design has moved toward more wearable form factors and more integrated sensing and control. In rehabilitation, review papers describe a broad range of sensing approaches (encoders, IMUs, contact and pressure sensors, and in some cases EMG or EEG) and control approaches that range from robust state-based strategies to more adaptive, intention-aware methods.[7] A systematic review focused on powered lower-limb exoskeletons after brain injury shows that clinical evidence remains heterogeneous and that adaptive strategies are not yet the dominant pattern in clinically reported devices, despite substantial research interest.[8]

In personal mobility, many of the same control and sensing ideas must work under less predictable conditions: turns, speed changes, start–stop transitions, stairs, and unexpected events. Studies and reviews make clear that even when assistance reduces metabolic cost in controlled trials, real-world adoption depends on long-wear comfort, stable behaviour during transitions, and serviceability.[9] In industry, variability is amplified by workflow constraints: a device can show benefits in a controlled task and still fail in real stations if it interferes with movement, slows cycle time, or causes discomfort during long wear.[10]

2.3 How the report is organized

The review is structured by application domain: rehabilitation, personal mobility, and industrial use. Sections 4-7 describe user needs, system families, enabling technologies, and validation evidence within each domain. Section 8 summarises the main technology gaps and maps cross-domain opportunities.

---

[5] Brunelli et al., 2025. *Review of upper-limb occupational exoskeletons: From technology to assessment.* International Journal of Industrial Ergonomics, 110, 103815.
[6] Crea et al., 2021. *Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces.* Wearable Technologies, 2, e11.
[7] Li et al., 2021. Review on control strategies for lower limb rehabilitation exoskeletons. IEEE Access, 9, 123040–123060.
[8] de Miguel-Fernández et al., 2023. Control strategies used in lower limb exoskeletons for gait rehabilitation after brain injury: a systematic review and analysis of clinical effectiveness. Journal of NeuroEngineering and Rehabilitation, 20(1), 23.
[9] Zhou et al., 2024. Review of lower-limb (quasi-) passive exoskeletons for human augmentation. IEEE Access.
[10] Baldassarre et al., 2022. Industrial exoskeletons from bench to field: Human-machine interface and user experience in occupational settings and tasks. Frontiers in Public Health, 10, 1039680.

3. Scope, Definitions, and Abbreviations

3.1 Purpose and scope of this review

This report reviews wearable exoskeletons across three application domains:

1. Rehabilitation exoskeletons used as clinical tools to deliver gait training and related therapeutic practice under structured protocols and supervision.[11]
2. Personal mobility exoskeletons used to support everyday mobility in the community (walking, stairs, inclines, and other daily barriers) and, in some studies, mobility performance augmentation (walking or running economy, jumping, or sport-like actions).[12]
3. Industrial exoskeletons used at work to reduce physical demands during manual handling, overhead tasks, and sustained awkward postures (including wearable chairs and squat-assist devices).[13]

For each domain, the report covers: user needs and use-cases, state of the art, technology approaches, validation evidence, and technology gaps and opportunities.

3.2 Definitions used in this report

3.2.1 Wearable exoskeleton

In this report, a wearable exoskeleton is a body-worn mechanical system that applies assistive forces or torques to one or more joints or body segments through a human–device interface (for example, straps, cuffs, braces, boots, or textile attachments). [14] Designs range from rigid link structures to soft or quasi-passive devices and may be passive, quasi-passive, or actively powered.

3.2.2 Rehabilitation exoskeleton

A rehabilitation exoskeleton is used primarily to deliver therapeutic practice, most often gait training, for people with neurological injury or disease.[1] The dominant clinical model involves supervised sessions in rehabilitation centres, using either treadmill-based platforms (often with BWS) or wearable overground devices.

---

[11] Plaza et al., 2023. Wearable rehabilitation exoskeletons of the lower limb: analysis of versatility and adaptability. Disability and Rehabilitation: Assistive Technology, 18(4), 392–406.
[12] Sawicki et al., 2020. The exoskeleton expansion: improving walking and running economy. Journal of NeuroEngineering and Rehabilitation, 17(1), 25.
[13] Perera et al., 2023. Exoskeletons for manual handling: A scoping review. IEEE Access, 11, 115568–115598.
[14] Ali et al., 2021. Systematic review of back-support exoskeletons and soft robotic suits. Frontiers in Bioengineering and Biotechnology, 9, 765257.

In scope. Powered lower-limb and trunk-related rehabilitation devices and associated sensing and control approaches, including emerging directions such as intention recognition and BCI-triggered walking.[7]

Out of scope. Industrial back supports used purely for occupational load reduction and military augmentation systems not evaluated as rehabilitation tools in the papers used for this report.[11]

3.2.3 Personal mobility exoskeleton

A personal mobility exoskeleton is used to support everyday mobility in the community. The main intent is not therapy dose delivery, but practical function: walking longer, managing daily barriers such as stairs and inclines, reducing effort, and improving confidence and safety in daily environments.[2]

In scope. Devices and studies aimed at community mobility support (including older-adult community programmes and barrier-task studies such as stairs and inclines), as well as passive, quasi-passive, and powered wearable systems evaluated for walking or running economy when the device and evaluation constraints are clearly relevant to personal use (mass, mass placement, comfort, durability, and safe behaviour during transitions). It also includes studies that focus on safety-relevant mobility behaviour such as balance recovery assistance when presented as wearable lower-limb support.

Out of scope. Industrial exoskeletons intended for workplace exposure reduction (covered under the industrial domain) and clinical rehabilitation studies where the primary goal is therapy delivery in supervised clinical programmes (covered under the rehabilitation domain), even if similar joints or hardware concepts are involved.

3.2.4 Industrial exoskeleton

An industrial exoskeleton is used to reduce physical demands during work tasks. Typical targets include overhead work (shoulder and upper-limb supports), manual handling and trunk flexion (back supports), and sustained awkward postures such as squatting or kneeling (including wearable chairs and squat-assist devices).[2]

In scope. Passive, quasi-passive, and powered devices evaluated for workplace tasks, including back-support and shoulder-support systems and lower-limb posture supports such as wearable chairs and squat-assist exoskeletons. It also includes the industrial evidence base on evaluation methods, benchmarking, worker acceptance, and field deployment pathways, including lab-to-field limitations and standardisation needs.

Out of scope. Clinical rehabilitation use of exoskeletons for therapy delivery (covered under the rehabilitation domain) and personal mobility assistive use in home or community settings (covered under the personal mobility domain), even if similar joints are targeted.

3.3 Evidence interpretation

Evidence is interpreted using the following principles:

1. **Context.** Results from laboratory test and supervised protocols are interpreted as evidence of effect under controlled conditions, not as evidence of long-term real-world use. This distinction is especially important in industrial studies (lab versus workplace) and in personal mobility (supervised trials versus daily use).

2. **Outcomes are interpreted within the purpose of the domain.**
   - Rehabilitation evidence emphasises functional mobility and independence outcomes commonly used in clinical trials.
   - Personal mobility evidence emphasises functional community outcomes (speed, endurance, balance) and locomotion economy depending on the study design.
   - Industrial evidence emphasises indirect measures of physical exposure (such as EMG and posture/kinematics) and user experience, with limited long-term injury outcomes.

3. **Domain overlap is handled explicitly.** Some technologies can appear in more than one domain (for example, lower-limb devices that could be used in supervised rehab and also tested for community mobility). When overlap exists, the report assigns the discussion to the domain that matches the study's stated goal and evaluation context.

3.4 Abbreviations

The following abbreviations are used in the remainder of this report:

- **ADL** – activities of daily living
- **BBS** – Berg Balance Scale
- **BCI** – brain–computer interface
- **BWS** – body-weight support
- **EEG** – electroencephalography
- **EMG / sEMG** – (surface) electromyography
- **FES** – functional electrical stimulation
- **FAC** – Functional Ambulation Category
- **FGA** – Functional Gait Assessment
- **FIM** – Functional Independence Measure
- **IMU** – inertial measurement unit
- **MCID** – minimal clinically important difference
- **PPE** – personal protective equipment
- **QUEST** – Quebec User Evaluation of Satisfaction with Assistive Technology
- **ROI** – return on investment
- **SCI** – spinal cord injury
- **SCIM** – Spinal Cord Independence Measure
- **TUG** – Timed Up and Go
- **WISCI-II** – Walking Index for Spinal Cord Injury II
- **10MWT / 6MWT / 2MWT** – 10-metre / 6-minute / 2-minute walk test
- **WMSD** – work-related musculoskeletal disorder

4. User Needs and Use-Cases

This section summarises the main user needs that shape exoskeleton design and evaluation in rehabilitation, personal mobility, and industrial work. It focuses on the practical goals, the tasks and environments that drive requirements, and the constraints that most often limit adoption.

Table 1 summarises user needs, task demands, operational constraints, and adoption drivers across the three domains.

Table 1. User needs and use-case matrix (Section 4 overview)

Domain	Target users and settings	Primary goals	Representative tasks and environments	Operational constraints and risks	Success criteria and adoption drivers
Rehabilitation exoskeletons	People with neurological gait impairment; evidence and clinical programmes are dominated by SCI and stroke, with smaller coverage of other conditions.[1] Primarily delivered in supervised inpatient/outpatient rehab services, with interest in less supervised community-oriented use increasing requirements on ease of use and safety.[11]	Deliver high-repetition stepping/standing practice when independent gait is limited; improve functional walking and mobility-related independence; support posture and trunk control during walking; reduce therapist physical burden and improve repeatability of training.[1]	Treadmill-based gait training often supported by BWS; wearable overground practice to expose users to postural control demands; hybrid overground with external safety support to bridge safety and function.[1]	High setup and fitting burden; don/doff time limits throughput; safety demands increase when moving beyond steady cycles and into transitions; learning/adaptation by user and staff is not automatic; heterogeneous protocols limit cross-device comparison.[15]	Safe delivery within clinical workflows; reliable therapist operation; measurable gains in standard functional outcomes used in the literature, without unacceptable operational burden.[8]
Personal mobility exoskeletons	Daily mobility users outside the clinic; many studies focus on older adults and community settings; evidence also includes healthy-user and performance-oriented studies when constraints are relevant to personal feasibility (mass, comfort, durability, transition safety).[16]	Support everyday walking and community mobility; reduce effort/fatigue (often via locomotion economy); enable barrier tasks (stairs, inclines, transfers); improve stability and safety under real variability.[2]	Community walking in realistic environments (hallways, ramps, curbs, stairs, multi-terrain); stairs/inclines as high-demand barriers; controlled walking/running economy trials; transition/non-steady gait cases; integration with	"Livability" constraints dominate: worn mass and mass placement can erase benefit; durability/serviceability can be limiting; benefits may require adaptation/training; safety must hold under non-steady events; acceptance depends on comfort, appearance, dignity, and fit with routines.[17]	Clear benefit with low daily burden; fast, repeatable setup and comfortable wear; manageable maintenance; support for learning; safe behaviour during transitions; ability to coexist with existing aids and routines.[18]

[15] Butnaru, 2021. Exoskeletons, rehabilitation and bodily capacities. Body & Society, 27(3), 28–57.
[16] del Rio Carral et al., 2022. Are functional measures sufficient to capture acceptance? A qualitative study on lower limb exoskeleton use for older people. International Journal of Social Robotics, 14(3), 603–616.
[17] Wang et al., 2024 (October). Using hip assisted running exoskeleton with impact isolation mechanism to improve energy efficiency. In 2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 214–220. IEEE.
[18] Lee et al., 2022. Effect of exercise using an exoskeletal hip-assist robot on physical function and walking efficiency in older adults. Journal of Personalized Medicine, 12(12), 2077.

			existing mobility aids where relevant.[2]		
Industrial and occupational exoskeletons	Workers exposed to repeated/sustained physical demands; common sectors include manufacturing/logistics and construction (with PPE and uneven terrain constraints). Real workflows involve mixed tasks and frequent transitions.[13]	Reduce physical exposure linked to WMSD risk factors; offload targeted regions during key task families; maintain productivity and avoid interference; support safe, acceptable all-shift wear. Acute exposure reductions are reported; long-term prevention impact remains uncertain due to limited long-duration field data.[3]	Three dominant task families: overhead work/repetitive reaching (shoulder supports); manual handling and trunk flexion (back supports); sustained awkward postures (wearable chairs/squat assist).[5]	Comfort, heat, and fit drift across a shift; workflow interference and task mismatch can drive removal; safety and side effects are not consistently addressed; lab-to-field gaps due to variability and implementation factors; need for standardised evaluation and deployment processes.[19]	Net exposure reduction in targeted tasks without unacceptable interference; acceptable comfort/usability across realistic wear durations; deployment pathway with training, maintenance, hygiene, task selection, and monitoring of side effects; evaluation frameworks that support procurement beyond small pilots.[19]

4.1 Rehabilitation use-cases

4.1.1 Target users and settings

Rehabilitation exoskeletons are primarily used for people with neurological conditions that impair gait and upright mobility. Clinical reviews of widely used wearable rehabilitation exoskeletons show that published trials and clinical programmes are dominated by populations with spinal cord injury and stroke, with smaller evidence coverage for other neurological conditions.[1] Broader surveys of lower-limb neurorehabilitation exoskeletons also describe interest in additional groups such as cerebral palsy, and they emphasise that user needs are highly variable across impairment profiles and recovery stages.[20]

The dominant delivery setting is a supervised rehabilitation service (inpatient or outpatient), where an exoskeleton is one tool within a broader programme. The practical implication is that the device must fit into clinical workflow: it must be safe under supervision, usable by trained staff, and feasible within session time limits.[1] There is also clear interest in moving parts of exoskeleton-enabled practice toward less controlled settings (family-led, home-based, or community-oriented use), which raises requirements for simpler operation and robust safety outside gait labs.[20]

4.1.2 Primary goals

Across the rehabilitation literature, Rehabilitation use-cases are built around five core goals.

[19] Andrade, C. and Nathan-Roberts, D., 2022 (September). Occupational exoskeleton adoption and acceptance in construction and industrial work: a scoping review. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 66(1), 1325–1329. SAGE Publications.
[20] Li et al., 2024. A survey of wearable lower extremity neurorehabilitation exoskeleton: Sensing, gait dynamics, and human–robot collaboration. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 54(6), 3675–3693.

1. **Deliver high-repetition gait practice and upright training.** Rehabilitation exoskeletons are used to deliver repeated stepping, standing, and transfer-related practice, particularly where independent walking is not possible or requires multiple therapists.[1]
2. **Improve functional walking ability and mobility-related independence.** Clinical studies commonly measure walking speed and standard tests and scales, including outcomes such as 10MWT, 6MWT/2MWT, TUG, FAC, BBS, FIM, and Barthel Index. These outcomes reflect a focus on real functional capacity rather than isolated joint performance.[8]
3. **Support balance, posture, and trunk control during walking.** Overground wearable exoskeletons often require the user to actively manage trunk and pelvis to initiate and sustain stepping, which makes postural control a central requirement for safe practice.[1]
4. **Reduce therapist physical burden and improve repeatability of training.** Exoskeletons are often introduced to reduce the manual handling load on therapists while keeping gait practice structured and repeatable across sessions.[21]
5. **Enable progression from controlled practice to more functional walking.** As users improve, programmes often aim to progress from highly controlled stepping practice toward more functional walking demands, including overground practice that better resembles real-world ambulation.[22]

4.1.3 Representative tasks and environments

Rehabilitation exoskeleton practice occurs in several environment types, with different demands:

Treadmill steeping with BWS for controlled repetition.
This setting prioritises safety and repeatability. The user is guided through repeated gait cycles while body-weight can be partially supported.[1] The main advantage is controlled, high-repetition stepping practice; the main limitation is that the environment reduces real-world variability and can constrain movement patterns.

Overground walking with wearable exoskeletons for functional practice.
Overground devices allow walking practice on level ground and, depending on the device and user, can extend toward more community-like mobility demands. Because they are less constrained than treadmill platforms, they also place greater demands on postural control and safe weight shifting.[1]

Overground walking with added external safety support.
Some programmes add an external safety system (for example, a mobile support) so users can follow overground trajectories while staying within a safety envelope. Clinicians use this

[21] Wang et al., 2022. A review on the rehabilitation exoskeletons for the lower limbs of the elderly and the disabled. Electronics, 11(3), 388.
[22] Gupta et al., 2023. Gait training with robotic exoskeleton assisted rehabilitation system in patients with incomplete traumatic and non-traumatic spinal cord injury: A pilot study and review of literature. Annals of Indian Academy of Neurology, 26(Suppl 1), S26–S31.

option when users need the functional value of overground practice but are not ready for fully wearable, unsupported training.[22]

Engagement tools during repeated practice.
Sessions may add virtual or game-based feedback to keep repeated training tolerable and to support adherence. Engagement affects adherence. If users lose engagement, they often reduce effort or stop attending sessions, which limits effective repetition. Clinics therefore use virtual or game-based feedback to maintain participation, although the optimal dose for some virtual-task elements is still not well established.[23]

4.1.4 Operational constraints and risks

Rehabilitation use-cases are constrained by clinical reality. The main constraints for rehabilitation exoskeletons described in the literature are:

- **Setup time, fitting, and donning/doffing complexity.**
  Rehabilitation systems must be fitted quickly and repeatably. Slow donning/doffing and complex setup reduce throughput and can limit how often the device is used, regardless of its technical capability.[1]
- **Safe transitions and mode switching.**
  Real walking includes transitions (start/stop, speed changes, turning, stepping over obstacles). Control pipelines that require reliable mode switching become more stressed when moving beyond steady gait cycles.[24] This is a practical risk when systems move from controlled treadmill patterns toward less constrained overground use.
- **User adaptation and tolerance.**
  Rehabilitation use is not "plug-and-play." Users and clinicians often need a learning period to coordinate movement with the device, and tolerance can be limited by how forces are transferred through the interface and how the user experiences the device over time.[15]
- **Evidence heterogeneity.**
  Rehabilitation studies vary widely in dose, protocols, and outcome sets, and follow-up is limited in many cases.[8] This limits the ability to generalise "what works best" across devices and populations.

4.1.5 Success criteria and adoption drivers

A rehabilitation exoskeleton programme succeeds when it is safe, feasible in routine service delivery, and produces meaningful improvement in mobility outcomes relevant to the user group. In practice, that means the system can be delivered reliably by trained staff, supports repeated gait practice, and shows measurable change in standard mobility and independence outcomes without unacceptable operational burden.[1]

[23] Mathew et al., 2023. A systematic review of technological advancements in signal sensing, actuation, control and training methods in robotic exoskeletons for rehabilitation. Industrial Robot: The International Journal of Robotics Research and Application, 50(3), 432–455.
[24] Long et al., 2023 (March). Review of human-exoskeleton control strategy for lower limb rehabilitation exoskeleton. Journal of Physics: Conference Series, 2456(1), 012002. IOP Publishing.

4.2 Personal mobility use-cases

4.2.1 Target users and settings

Personal mobility exoskeletons are aimed at daily mobility outside the clinic. Many studies focus on older adults, where reduced mobility affects daily activities and social participation and increases concern about stability and falls.[16] Qualitative work in older people and caregivers frames exoskeletons as potential tools to support autonomy but also emphasises ambivalence and the need for learning and support.

Evidence also includes healthy-user studies and performance-oriented evaluations that target walking or running economy. These studies are included in this report because they address the same constraints that determine personal feasibility: wearable mass, mass placement, comfort, safe behaviour during transitions, and durability.[12]

4.2.2 Primary goals

Personal mobility use-cases cluster around four goals:

1. **Support everyday walking and community mobility.** Community-delivered programmes describe mobility tasks that go beyond standard walkways and include common real environments such as indoor corridors, ramps, curbs, stairs, and multi-terrain walking.[2]
2. **Reduce effort and fatigue during walking or running.** Many personal mobility devices aim to reduce the metabolic cost of walking or running under specific conditions, which can translate into longer walking capacity or reduced fatigue if the benefit holds during real use.[12]
3. **Enable barrier tasks that limit independence.** Stair ascent and incline walking are repeatedly framed as demanding daily-life barriers. Studies explicitly evaluate assistance in these tasks and report reductions in metabolic cost with assistance modes in older adults.[18] Other device papers focus on stair-climbing augmentation and quantify knee motion and torque requirements in stair ascent with load, illustrating why stairs drive higher assistance demands than level walking.[25]
4. **Improve safety and stability under real-world variability.** Several personal-mobility papers treat non-steady events as central design cases. For example, balance assistance research explicitly targets instability detection and recovery, reflecting the need for safe behaviour in unexpected events, not only steady walking.[26]

4.2.3 Representative tasks and environments

Personal mobility studies include several recurring task sets:

---

[25] Zhang et al., 2018 (July). Lower extremity exoskeleton for stair climbing augmentation. In 2018 3rd International Conference on Advanced Robotics and Mechatronics (ICARM), 762–768. IEEE.
[26] Hua et al., 2022. Assistance control of human-exoskeleton integrated system for balance recovery augmentation in sagittal plane. IEEE Transactions on Industrial Electronics, 69(1), 528–538. doi: 10.1109/TIE.2021.3050363.

Community walking tasks in realistic environments. Community programmes in older adults include tasks that reflect real mobility, such as multi-surface walking and progression toward speed changes, multidirectional stepping, inclines, stairs, and obstacle negotiation.[2]

Stairs and inclines as high-demand barriers. These tasks are evaluated as realistic daily barriers. In older adults, assistance modes have been tested during stair ascent and incline walking, with reported reductions in net metabolic energy cost.[18] Stair-focused exoskeleton designs report knee flexion and knee moment magnitudes under load, showing why stair assistance is mechanically demanding and often pushes designs toward higher torque capacity.[25]

Walking and running economy evaluations. A large body of work evaluates metabolic cost during walking or running under controlled conditions, including passive and quasi-passive designs and powered devices. Reviews summarise that economy improvements are possible, but depend on design, tuning, and evaluation conditions.[12] Specific passive hip devices report reductions in running metabolic cost and highlight the trade-offs involved when device mass is considered.[27]

Non-steady gait and transition cases. Switchable passive designs explicitly aim to engage assistance in stance and avoid resisting motion in swing, which reflects a core "transition" requirement for wearability.[28] Other work focuses on rapid recovery and balance assistance during instability events.[26]

Integration with existing mobility aids. Older-adult reviews and community studies indicate that real-world users may already rely on canes or walkers, which shapes how an exoskeleton must fit into daily routines and multi-aid use.[29]

4.2.4 Operational constraints and risks

Personal mobility adoption is constrained by "livability" factors that are more demanding than in supervised rehab. The main constraints for personal mobility exoskeletons described in the literature are:

- **Worn mass and mass placement.**
  Mass placed away from the body's centre of gravity can increase effort and reduce comfort and acceptance, which is especially important for running and long-wear use.[17] Designs that move heavier components toward the waist and transmit forces through cables are one practical strategy to keep distal mass low.[4]
- **Durability and serviceability.**
  Portable powered transmissions can shift the limiting factor from performance to wear life and maintenance. For example, twisted-string transmission work reports short

[27] Nasiri et al., 2018. Reducing the energy cost of human running using an unpowered exoskeleton. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26(10), 2026–2032.
[28] Dollar and Herr, 2008 (September). Design of a quasi-passive knee exoskeleton to assist running. In 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 747–754. IEEE.
[29] Gavrila Laic et al., 2024. A state-of-the-art of exoskeletons in line with the WHO's vision on healthy aging: From rehabilitation of intrinsic capacities to augmentation of functional abilities. Sensors, 24(7), 2230.

component lifetimes under high torque, which is incompatible with daily use unless serviceability is redesigned.[30]

- **User adaptation and training needs.**
  Some studies show that benefits stabilise only after a period of exposure. In older adults using an ankle exoskeleton, the minimum metabolic power and minimum muscle activation occurred after several minutes of adaptation, which implies that short "first minutes" may underestimate true benefit and that training and familiarisation matter for real use.[31] Qualitative evidence also stresses that older adults and caregivers expect a learning process and may perceive the technology as stressful or "futuristic" without support.[16]
- **Safety under variability and unexpected events.**
  Personal mobility includes turns, speed changes, and unexpected perturbations. Running-oriented clutch designs report failure modes under rapid deceleration and motivate explicit disable modes and careful transition handling.[32] Balance assistance work targets detection and recovery from instability, reinforcing the need to address safety beyond steady gait.[26]

4.2.5 Success criteria and adoption drivers

Personal mobility systems succeed when benefit is obvious, and burden is low. Evidence suggests that even when devices achieve measurable benefits in trials, users still request improvements in weight, noise, and design, factors that directly affect daily willingness to wear the system.[18] Adoption also depends on dignity, autonomy, and fit with routines, and may require progressive learning and support pathways rather than assuming immediate acceptance.[16] Long-term success therefore requires both technical performance and a realistic pathway for training, maintenance, and integration with existing mobility aids.

4.3 Industrial and occupational use-cases

4.3.1 Target users and work settings

Industrial exoskeletons are used by workers who perform tasks with repeated or sustained physical demands, where the goal is to reduce exposure linked to WMSD risk factors while maintaining safe work performance.[3] Evidence and early deployments commonly address manufacturing-like environments and logistics, with construction also covered as a domain with distinct constraints such as uneven ground and PPE requirements.[10]

A defining feature of industrial use is task variability: real workflows combine multiple postures and transitions, and performance in a single controlled task may not predict usability across a full shift.[6]

4.3.2 Primary goals

[30] Tan and Collins, 2025. Design of an ankle exoskeleton with twisted string actuation for running assistance. Wearable Technologies, 6, e34.
[31] Fang et al., 2022. Feasibility evaluation of a dual-mode ankle exoskeleton to assist and restore community ambulation in older adults. Wearable Technologies, 3, e13.
[32] Elliott et al., 2014. Design of a clutch–spring knee exoskeleton for running. Journal of Medical Devices, 8(3), 031002.

Industrial use-cases focus on 3 main goals:

1. **Reduce acute physical stress/strain in supported areas.** Evidence studies support acute reductions in physical stress/strain in the supported body area, but long-term prevention impact remains uncertain due to limited long-duration real-work evidence.[3]
2. **Reduce workload during targeted task families**. The main task families are overhead work (shoulder/upper-limb supports), manual handling and trunk flexion (back supports), and sustained awkward postures such as squatting or kneeling (including wearable chair and squat-assist systems).[14]
3. **Maintain productivity and avoid interference.** A practical requirement is that the device must not slow cycle time or block needed motions. Evidence repeatedly shows that benefits are clearer in static tasks and more variable in dynamic workflows where interference is more likely.[10]

4.3.3 Representative tasks and environments

Industrial use-cases can be described in the following task categories:

Overhead work and repetitive reaching.
Shoulder supports aim to offload effort during sustained or repeated arm elevation. Mechanically, this requires compatibility with complex shoulder motion and preservation of workspace so that tool access and cross-body reach are not compromised.[33]

Manual material handling and trunk flexion.
Back-support systems aim to reduce loading during lifting and forward bending. The industrial design space includes passive and powered devices and uses different evaluation approaches, which affects comparability and deployment choices.[14]

Posture support for kneeling, stooping, and squatting.
Wearable chair and squat-assist systems support prolonged or repeated low postures. Reported effects include reductions in muscular demands and plantar pressure in supported postures, alongside comfort and perceived safety barriers that matter for field use.[34]

Construction work under variable conditions.
Construction settings introduce additional variability (uneven ground, climbing, weather, PPE) and require trade-level matching of device type to task demands; a construction review explicitly maps exoskeleton types to construction trades with benefits and challenges.[9]

4.3.4 Operational constraints and risks

Industrial constraints are often “make or break” for deployment. The main constraints for industrial exoskeletons described in the literate are:

[33] Anaya-Reyes et al., 2023. Shoulder-support exoskeletons for overhead work: Current state, challenges and future directions. IEEE Transactions on Medical Robotics and Bionics, 5(3), 516–527.
[34] Kuber et al., 2023. A systematic review on lower-limb industrial exoskeletons: Evaluation methods, evidence, and future directions. Annals of Biomedical Engineering, 51(8), 1665–1682.

- **Comfort, heat, and fit across a shift.**
  Worker acceptance depends strongly on discomfort, ease of use, and learnability, and these factors are repeatedly highlighted in acceptance-focused reviews.[19] Fit issues can also change across a shift as clothing and strap tension change, which can create hot spots and reduce willingness to continue wearing the device.
- **Workflow interference and task mismatch.**
  Many jobs involve mixed tasks and frequent transitions. If the device's assistance envelope does not match the actual duty cycle, workers may remove it during parts of the job, reducing real exposure benefit.[10]
- **Limited standardisation and safety coverage in studies.**
  Industrial evaluation methods are not standardised, samples are often not representative, and safety aspects are not consistently addressed. Side effects in non-target body regions also require attention.[35]
- **Implementation factors beyond the device.**
  Large-scale adoption requires field validation in real work contexts and must connect to risk assessment methods and workplace guidelines, not only short pilots.[6]

4.3.5 Success criteria and adoption drivers

Industrial success is defined by combined benefit and practicality: reduced exposure during targeted tasks, no unacceptable interference with work, acceptable comfort across realistic wear durations, and an implementation pathway that includes training, maintenance, and clear task selection.

Evidence mapping work also shows that as evaluation moves toward more applied tasks, user experience measures become increasingly important, reflecting that adoption depends on more than biomechanical endpoints alone.[36] Finally, multiple reviews call for multi-criteria, standardised evaluation frameworks that combine metrics, tasks, and postures to support decisions beyond small pilots and to reduce the lab-to-field gap.[37]

[35] Hoffmann et al., 2022. Methodologies for evaluating exoskeletons with industrial applications. Ergonomics, 65(2), 276–295.
[36] De Bock et al., 2022. Benchmarking occupational exoskeletons: An evidence mapping systematic review. Applied Ergonomics, 98, 103582.
[37] Golabchi et al., 2022. A systematic review of industrial exoskeletons for injury prevention: efficacy evaluation metrics, target tasks, and supported body postures. Sensors, 22(7), 2714.

5. State of the Art Review

This section reviews current exoskeleton systems in rehabilitation, personal mobility, and industrial use. It summarises the main system families and representative devices, the typical validation approaches used in each domain, and the outcomes most often reported in the literature.

5.1 Rehabilitation exoskeletons

5.1.1 Evidence base and scope of systems

Rehabilitation exoskeleton evidence is dominated by powered lower-limb systems designed for gait training and upright mobility practice in clinical populations, especially stroke and spinal cord injury.[1] A large study base exists, but it is heterogeneous in dose, outcomes, and device configuration, and only a minority of studies include follow-up. For example, one systematic review screened 1,648 records, included 159 full-text articles, and identified 43 powered lower-limb exoskeletons reporting control details plus clinical or biomechanical outcomes; in that same review only 12.58% of studies included follow-up (typically around 4 months).[8] Across published rehabilitation systems, the most common evaluation model is supervised use in rehabilitation services, often as a block of sessions integrated into a broader therapy programme.

5.1.2 Main system categories

Rehabilitation exoskeletons can be grouped into two categories based on how they deliver walking practice.

1. **Category A: treadmill-based or platform-based gait robotics (often with BWS).** These systems guide the user through repeated gait cycles while a harness provides adjustable support and fall protection. They are designed for high repetition and controlled stepping practice and are common in early-stage rehabilitation where safety and repeatability are priorities.[38]
2. **Category B: wearable overground exoskeletons (often with walking aids).** These devices move with the user over level ground and are often used to expose the user to postural and balance demands that are closer to real walking than treadmill-constrained cycles. Depending on design and user ability, they may be used with crutches or walkers.[1]

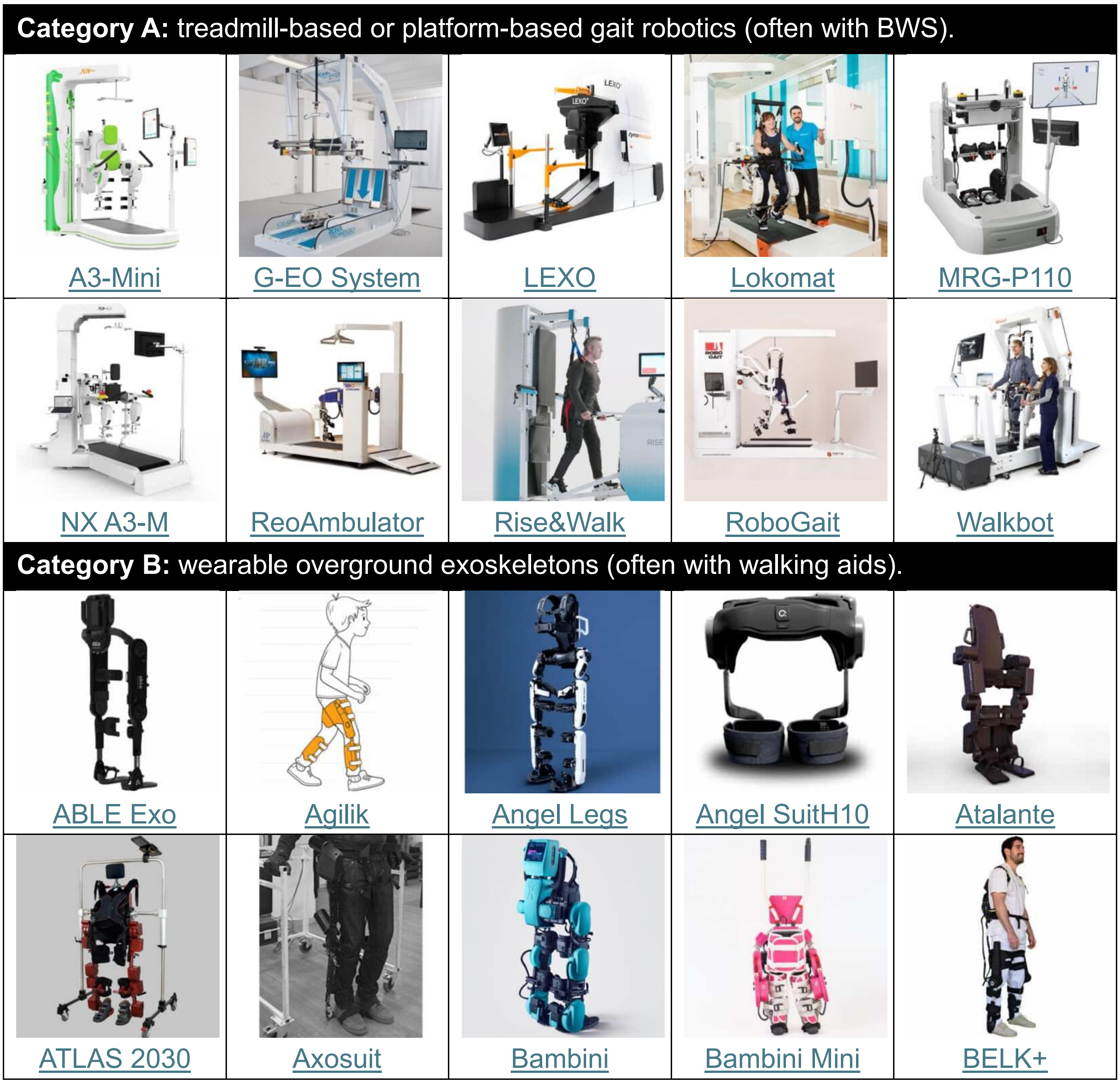
Overground wearable exoskeleton training (Category B) is often delivered with an external safety system that provides fall protection and, in some cases, partial body-weight support (for example, an overhead track, ceiling rail, or mobile fall-arrest frame). This setup is a common

[38] Zhou et al., 2021. Lower limb rehabilitation exoskeleton robot: A review. Advances in Mechanical Engineering, 13(4), 16878140211011862.

clinical configuration used to keep overground practice functional and task-relevant while increasing safety for users who are not yet ready to train with a fully wearable system alone.[22] In parallel, a smaller but important group of rehabilitation systems provides trunk or whole-body support to stabilise upright posture and stepping, reducing the need for balance management with crutches compared with standard wearable overground devices.[1]

Figure 1 lists commercially available rehabilitation gait exoskeleton systems under each category. The list focuses on products that are marketed for clinical gait training and are used in structured rehabilitation programmes.

Figure 1. Commercial rehabilitation gait exoskeletons by training mode (treadmill/platform with BWS, and wearable overground).



 COSMOS	 Ekso Indego	 Ekso NR	 ExoAtlet II	 ExoLite
 ExoMotus M4	 EXPLORER	 FreeGait	 H-MEX	 HAL Lower Limb
 HANK	 KidGo	 Myosuit	 ReWalk	 REX
 Roki	 Rokids	 Trexo	 UGO210	 UGO220
 Walk-On Suit	 XoMotion			

5.1.3 Representative examples and what they demonstrate

A practical way to understand the rehabilitation state of the art is to look at what is routinely evaluated in clinical trials and what capabilities are treated as clinically meaningful.

Overground wearable devices evaluated with functional outcomes.
Clinical trials of widely used wearable rehabilitation exoskeletons have been synthesised with a focus on functional outcomes across devices such as Atalante, Atlas, Ekso, HAL, Indego, ReWalk, and Rex. Across these systems, the dominant reported outcomes are functional walking tests, independence measures, and safety/feasibility indicators under supervised delivery.[1]

Overground training as a postural control challenge.
In overground use, the user must coordinate trunk and pelvis with stepping. A reported example is that overground training with Ekso can elicit substantial trunk muscle activation in users with high-thoracic motor-incomplete spinal cord injury, highlighting that the exoskeleton does not replace the need for trunk control and can act as a postural challenge within safe supervision.[1]

Hybrid overground mobility with safety constraints.
In incomplete spinal cord injury, overground training with safety support has been reported as feasible and safe in structured delivery, with device malfunctions occasionally requiring engineering support, an operational point that matters for real service delivery.[22]

BCI-triggered or BCI-modulated exoskeleton walking (experimental).
EEG-based BCI approaches have been used to trigger or modulate exoskeleton-assisted walking in clinical contexts, aiming to link cortical activity and gait-related movement. This remains experimental but illustrates the current direction of "intent from the nervous system" as a control input rather than relying only on mechanical sensors.[39]

5.1.4 What outcomes are typically reported

The rehabilitation state of the art is strongly shaped by what clinics can measure reliably and what regulators and services accept as meaningful.

Functional walking and mobility outcomes dominate. A systematic review of powered lower-limb exoskeletons after brain injury reports heavy use of standard gait and mobility measures. In that evidence base, gait speed was reported in 37.74% of studies (with cadence in 25.16% and step length in 23.27%). Common clinical measures included 10MWT (20.75%), 6MWT (16.98%), TUG (10.06%), FAC (29.56%), BBS (14.47%), FIM (8.81%), and Barthel Index (11.32%).[8]

Biomechanics and physiology are reported, but less consistently. Joint kinematics were reported in 44.65% of studies, while energy expenditure was reported in 10.69% (often via oxygen consumption), and neural activity measures in about 6.29%, reflecting the practical reality that clinics prioritise functional tests and scales.[8]

EMG appears as a mechanism and adaptation measure. Surface EMG appeared in 20.75% of studies, often targeting key gait muscles (e.g., tibialis anterior, gastrocnemius, soleus, rectus femoris, vastus lateralis, semitendinosus).[8]

5.1.5 Maturity and current deployment pattern

The rehabilitation exoskeleton space includes commercially deployed systems and a large research pipeline. The deployed systems tend to prioritise robust operation and therapist-

[39] Colucci et al., 2022. Brain–computer interface-controlled exoskeletons in clinical neurorehabilitation: ready or not?. Neurorehabilitation and Neural Repair, 36(12), 747–756.

manageable workflows, and many clinical implementations still rely on state-based control and predictable gait patterns rather than fully adaptive, user-specific assistance.[11] Research trends emphasise richer sensing and intent-aware control, but translation into routine clinical practice is constrained by operational burden, certification needs, and the difficulty of robust performance under user variability.[40]

5.2 Personal mobility exoskeletons

5.2.1 Evidence base and scope of systems

Personal mobility exoskeletons include devices intended to support everyday community mobility (especially in older adults) and devices evaluated for locomotion economy in walking or running. The shared theme is that the user must carry the device during real movement, which makes mass, mass placement, comfort, and durability decisive design constraints.[16] A systematic review in older adults[29] highlights breadth across many study types (36 studies in that review) but also emphasises heterogeneity and a need for more evaluation in realistic home environments and ADL-like tasks.

5.2.2 Main system categories

Personal mobility systems can be grouped in two categories by what tasks they target.

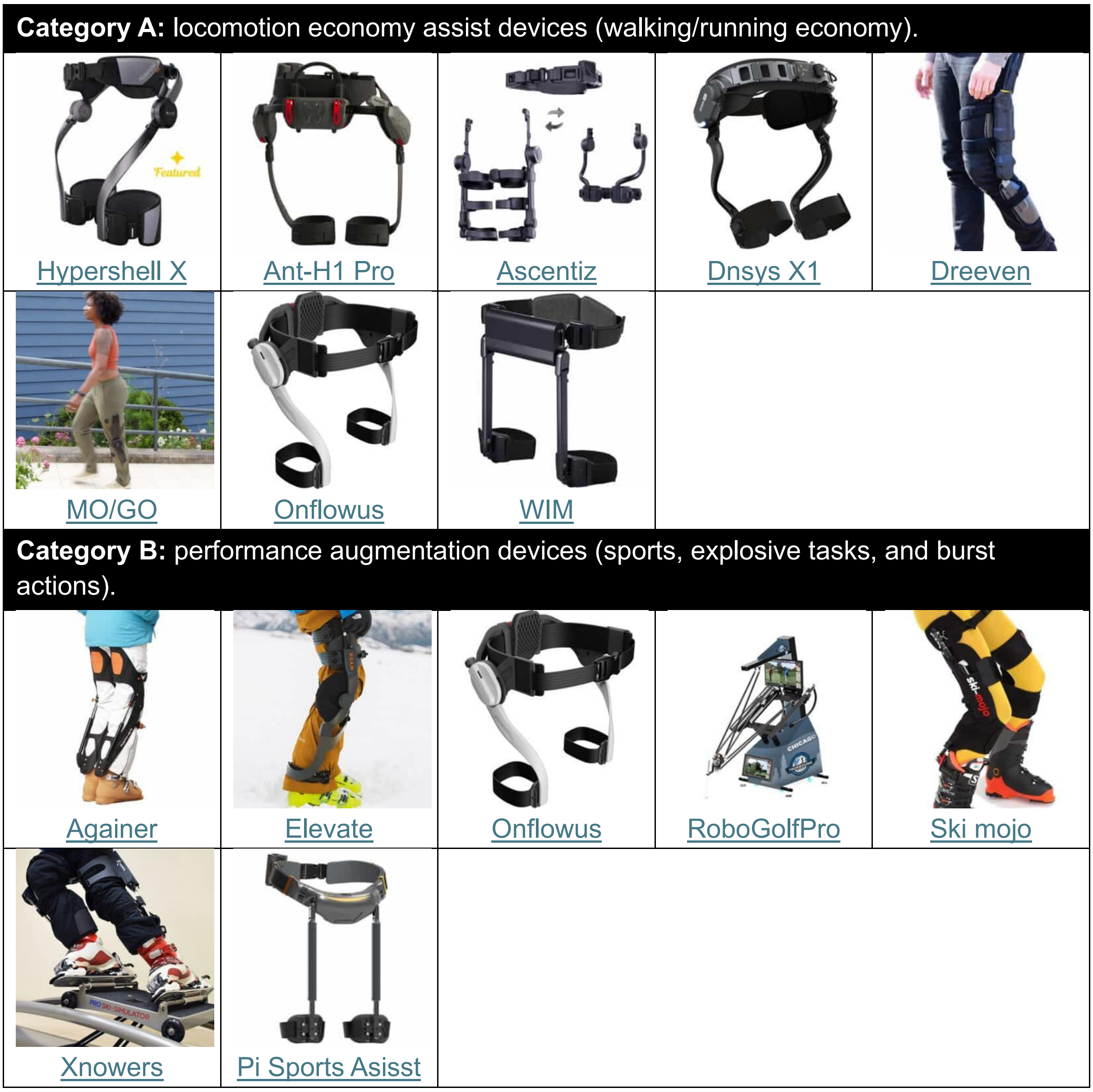
1. **Category A: locomotion economy assist devices (walking/running economy).**
   These systems are designed to reduce the energetic cost of steady locomotion. Most are passive or quasi-passive designs that store and return energy (often with switchable engagement to avoid swing interference), aiming to reduce metabolic cost with minimal powered hardware.[28] A review of quasi-passive lower-limb exoskeletons screened 203 papers (2014–2024) and retained 22 publications; it summarised net metabolic cost reductions of 3.3–8.6% for walking and 4.0–8.0% for running, depending on the device and protocol.[38]
2. **Category B: performance augmentation devices (sports, explosive tasks, and burst actions).**
   A smaller branch of personal mobility research targets performance outcomes beyond steady locomotion, such as jumping, kicking, sprint-like assistance, or other burst actions. In this category, benefits depend strongly on the action, user technique, and the assistance mechanism, and evaluation often focuses on peak performance metrics rather than endurance or economy.

Beyond these two device categories, the literature also reports barrier-task assistance systems that use rigid structures and joint actuation to support high-demand tasks such as stairs, inclines, and repeated sit-to-stand variants, where required joint moments and joint excursions exceed those of level walking.[38]

[40] Yao et al., 2024. Advancements in Sensor Technologies and Control Strategies for Lower-Limb Rehabilitation Exoskeletons: A Comprehensive Review. Micromachines (Basel), 15(4), 489. doi: 10.3390/mi15040489.

Figure 2 lists commercially available personal mobility exoskeleton systems grouped by the two task-driven categories: locomotion economy support and performance augmentation.

Figure 2. Commercial personal mobility exoskeletons grouped by locomotion economy support and performance augmentation.



5.2.3 Representative examples and what they demonstrate

Community mobility programmes in older adults.

Community programmes are important because they test exoskeleton use in real walking environments, not only lab corridors. A community-delivered programme in a senior living facility delivered 12 sessions (30 minutes per session over 4–6 weeks) and progressed beyond corridor walking to ramps, curbs, stairs, multi-terrain surfaces, and then speed changes, multidirectional stepping, inclines, and obstacle negotiation. It reported 10MWT improvements of 0.18 m/s and 0.21 m/s, 6MWT improvement of 62.5 m, BBS increase of 4 points, FGA increase of 5.1 points, and QUEST satisfaction of 4.5 ± 0.6, with no adverse events and no device-related falls.[2]

Assistance during daily barriers (stairs and inclines).
Daily-life barriers matter because they often determine whether a person can move independently in the community. In community-dwelling older adults, a hip exoskeleton intervention reported reduced net metabolic energy cost during stair ascent (12.80%) and inclined treadmill walking (21.66%) under assistance mode, showing that assistance can target daily barriers where demand is higher than level walking.[18]

Why stairs drive higher torque requirements.
Stairs are a key design driver because they require larger joint excursions and higher joint moments than level walking. Stair-focused device studies report large knee excursions and substantial knee moment requirements. For example, stair-ascent work reported knee flexion up to 85° and a knee moment up to 0.8 Nm/kg under a 30 kg load, illustrating the magnitude of assistance needed for barrier-capable mobility.[25]

Passive hip exoskeletons that support both walking and running.
Passive and quasi-passive designs aim to reduce effort without adding motors or batteries, but their benefits depend on tuning. An unpowered hip exoskeleton reported net metabolic-rate reductions of 8.2% ± 1.5% (walking) and 9.1% ± 1.3% (running) at separately optimised stiffnesses, and 7.2% ± 1.2% (walking) and 6.9% ± 0.8% (running) using a common stiffness.[38]

Passive hip running assistance with explicit mass accounting.
Mass can offset benefit, so some studies account for device mass when reporting economy outcomes. A passive hip exoskeleton study reported an 8.0% ± 1.5% reduction in metabolic cost versus no exoskeleton and 10.2% ± 1.5% when device mass was accounted for; the same work reported total mass around 1.8 kg, illustrating the mass–benefit trade-off.[27]

Portability through proximal actuation and cable transmission.
To improve wearability, several designs place heavier components near the waist and transmit force distally to keep the foot and shank light. An ankle exoskeleton design placed actuation at the waist and transmitted force via Bowden cables to reduce distal mass; it reported that 300 N cable force with an 18 cm lever arm could generate ~52 Nm ankle torque, with 59% transmission efficiency.[4]

Durability as a limiting factor for powered running assistance.
For daily-use systems, durability and serviceability can become the limiting factor even when assistance magnitude is achievable. A powered ankle running exoskeleton using a twisted-string transmission reported a minimum string lifespan of about 3 min 22 s under 43 Nm peak torque assistance, demonstrating that durability and serviceability can be the bottleneck even when assistance magnitude is achievable.[30]

Non-steady gait and transition safety in passive systems.
Real mobility includes non-steady events (starting, stopping, rapid deceleration), so passive systems must avoid adding resistance at the wrong time. Switchable passive knee concepts and clutch-based systems show the central requirement of avoiding swing interference while providing stance-phase assistance, and they also highlight that non-steady events such as rapid deceleration can create failure modes that require explicit safe disengagement logic.[28]

Balance recovery as a wearable control problem.
Community mobility includes unexpected disturbances (for example, a slip, a trip, or a sudden loss of balance), so some personal mobility research treats balance recovery as a core control requirement rather than a secondary feature. In one study, the exoskeleton control strategy detects when the user becomes unstable and then applies assistive action intended to help the user regain balance. The authors report reductions in balance recovery time on the order of 160–580 ms in their experimental setup. They also report that the control computation was fast enough for real-time operation, solving each update in about 2 ms while running at 200 Hz.[26]

Mobility-related performance augmentation beyond steady gait.
A smaller branch of the literature targets performance outcomes rather than endurance or steady walking economy, and results depend on technique and adaptation. A passive knee exoskeleton study reported a 6.4% increase in jump height after instruction and adaptation, illustrating that user technique and learning can change outcomes.[41] A separate lower-limb exoskeleton design targeted kicking and reported improvements including 53% higher kicking force, 31% higher muscular strength, and 12% increased jumping height, illustrating a “burst assistance/performance” branch distinct from steady-state walking economy.[42]

5.2.4 What outcomes are typically reported

Personal mobility studies report three main outcome families.

1. **Functional mobility and balance outcomes in older adults.**
   Community programmes and older-adult trials report outcomes such as walking speed (10MWT), endurance (6MWT), balance measures (BBS, FGA), functional tasks (e.g., 5x sit-to-stand), and satisfaction questionnaires (QUEST).[2]
2. **Metabolic cost and muscle activity outcomes in controlled evaluations.**
   Economy-focused studies report metabolic outcomes (often net metabolic cost) and may also report EMG or other physiological indicators. Adaptation studies show that some benefits stabilise only after minutes of exposure; for example, in older adults using an ankle exoskeleton, the minimum metabolic power occurred at 6.6 ± 1.6 min, and 4/5 participants reduced net metabolic power by up to 19% under assistance.[12]

Task-specific mechanics for barrier tasks.
Barrier-focused device studies report kinematics and torque requirements during stairs or loaded movement, which is essential for engineering realistic assistance capacity.[25]

5.2.5 Maturity and current deployment pattern

Personal mobility has a growing evidence base, but most published work remains supervised and time-limited. Community programmes represent an important shift toward realistic

[41] Ben-David et al., 2022. Passive knee exoskeleton increases vertical jump height. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 1796–1805.
[42] Wang et al., 2025. Control Method of Upper Limb Rehabilitation Exoskeleton for Better Assistance: A Comprehensive Review. Journal of Field Robotics, 42(4), 1373–1387.

environments, but long-duration daily adoption is still constrained by wearability and support requirements, including comfort, noise, weight, durability, and the need for progressive learning and acceptance.[16]

5.3 Industrial exoskeletons

5.3.1 Evidence base and scope of systems

Industrial exoskeletons are used to reduce physical demands during work tasks, with the immediate target being exposure reduction rather than clinical recovery or general mobility. The evidence base includes many lab studies, shorter workplace pilots, and multiple review efforts, but long-duration field evidence remains limited.[6]

Industrial literature is dominated by passive systems, especially for shoulder/upper-limb support and back support, because they are lighter and avoid battery charging and maintenance logistics.[10]

5.3.2 Main system categories

Industrial exoskeletons can be grouped in three categories by target body region and task family.

1. **Category A: shoulder and upper-limb supports (overhead work and repetitive reaching).**
   These systems aim to reduce load during arm elevation and overhead tasks. The core engineering challenge is compatibility with shoulder kinematics and preservation of workspace and tool access.[33]
2. **Category B: back and trunk supports (manual handling and forward bending).**
   These devices aim to reduce loading during lifting and sustained trunk flexion. The design space includes passive, powered, and quasi-passive systems.[14]
3. **Category C: lower-limb posture supports (squatting, kneeling, prolonged low postures).**
   Wearable chairs and squat-assist systems support prolonged or repeated low postures and aim to reduce local muscle demands and discomfort.[34]

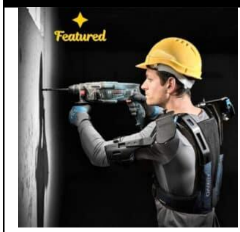
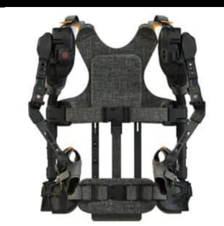
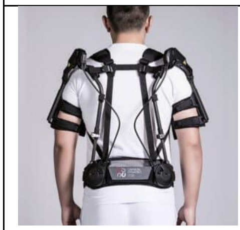
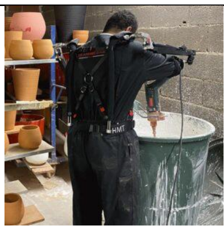
In addition to these three device categories, a smaller body of work examines active industrial exoskeletons that use intention prediction to better align assistance timing with the user's movement. One systematic review of intent prediction for active upper-limb industrial exoskeletons included 29 studies and reported prediction windows ranging from about 450 ms before to 660 ms after motion onset, illustrating the timing constraints that intent-aware control must meet in variable work tasks.[43]

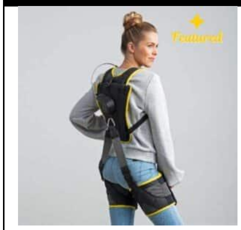
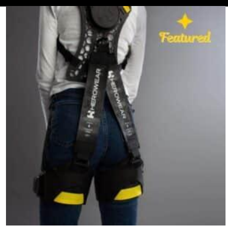
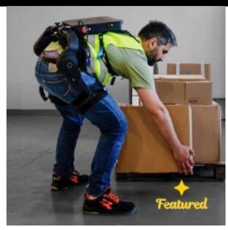
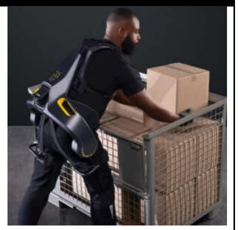
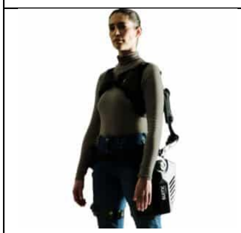
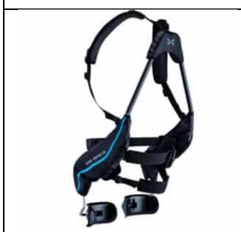
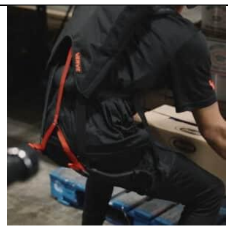
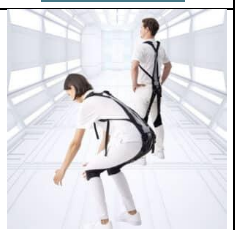
[43] Hochreiter et al., 2025. Intention prediction for active upper-limb exoskeletons in industrial applications: A systematic literature review. Sensors (Basel, Switzerland), 25(17), 5225.

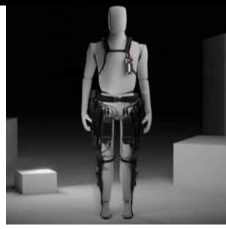
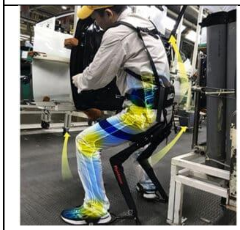
Figure 3 lists commercially available industrial exoskeleton systems grouped by the three body-region categories used in this section: shoulder/upper-limb supports, back/trunk supports, and lower-limb posture supports.

Figure 3. Commercial industrial exoskeleton systems grouped by shoulder/upper-limb, back/trunk, and lower-limb posture support categories.

Category A: shoulder and upper-limb supports (overhead work and repetitive reaching).

 DeltaSuit	 OmniSuit	 Agadexo	 Ant-A1	 Ant-A10
 CDYS	 Ercura Arms	 EVO	 EXO-O1	 EXO-S
 EXO-T-22	 EXO ARMS	 EXO SHOULDER	 Hapo FRONT	 Hapo UP
 Holdupper	 IX SHOULDER AIR	 LIGHT	 MAPS-E	 MATE-XT
 Muscle Upper	 PLUM	 S700	 Shiuva Exo	 ShoulderX

 Skelex 360	 TASK AR 3.0	 Titan Arms	 UPLIFT	 X-Rise
Category B: back and trunk supports (manual handling and forward bending).				
 Apex	 Apex 2	 MOVI	 Ant-P1	 Apogee
 Apogee+	 BES-HV	 BES-P	 Biolift	 BionicBack
 CareExo Lift	 CDYB-Fit	 Cray X	 Element Exo	 HAL Lumbar Support
 IX BACK	 IX BACK AIR	 JaipurBelt	 Muscle Suit Every	 Muscle Suit Exo-Power
 Muscle Suit GS-BACK	 Muscle Suit Soft-Light	 Muscle Suit Soft-Power	 SafeLift	 SUPPORT JACKET Bb+

 UPLIFT	 UPLIFT Lite	 WIBS		
Category C: lower-limb posture supports (squatting, kneeling, prolonged low postures).				
 ArchelisFX	 ArchelisFXS	 Chairless Chair 2.0	 E1	 legX
 Sit Anytime PHEL1				

5.3.3 Representative examples and what they demonstrate

Acute effects versus long-term outcomes

Industrial studies most often report short-term changes in physical demand during specific tasks, and meta-analytic evidence supports reductions in acute physical stress/strain in the body region supported by the exoskeleton. At the same time, long-term health and prevention outcomes remain uncertain because long-duration field evidence and injury endpoints are limited in the current literature.[3]

Task fit and workflow variability

Industrial performance is strongly shaped by how well the device matches the task and the real workflow. Reviews of field and applied studies report clearer benefits in more static task segments, while results become more variable in dynamic work that includes frequent transitions, cross-body reach, walking between stations, or constrained spaces where the device can interfere with movement or tool use.[10]

Lower-limb posture support: magnitude of effects and barriers to use

Lower-limb posture supports (wearable chairs and squat-assist systems) can produce large short-term reductions in physical demand during supported postures, but comfort and perceived safety strongly influence whether workers will wear them. A review of 23 articles reports reductions in lower-body muscular demands of roughly 30–90%, plantar pressure reductions of about 54–80% in supported postures, and reductions in low-back demands around 37%. The same review notes discomfort and “unsafe feeling” as barriers and highlights the need to evaluate fatigue, metabolic rate, stability, and walking/sitting interchangeability.[34]

Adoption and implementation in real workplaces

Industrial adoption is shaped by worker experience and how deployment is organised. Acceptance-focused reviews report that discomfort, ease of use, learnability, and organisational factors such as voluntariness, training, and maintenance planning influence whether devices are worn consistently.[19] Roadmap work further emphasises that scale-up requires product-specific field validation and integration into workplace risk assessment and guidance, not only short pilots or lab studies.[6]

5.3.4 What outcomes are typically reported

Industrial evaluations commonly report:

- **Exposure indicators:** EMG and posture/kinematics are widely used to quantify changes during targeted tasks.
- **User experience:** perceived exertion, discomfort, usability, and willingness to use are frequently reported and become increasingly important as studies become more applied.
- **Task performance indicators:** task time and perceived interference are often included, especially in workplace-oriented work where cycle time matters.

Methodology-focused work also highlights inconsistency in study designs, limited representativeness of participant samples, and incomplete attention to safety aspects in many studies, which limits comparability across devices and contexts.[35] An evidence-mapping review identified 139 eligible studies spanning 33 back exoskeletons, 25 shoulder exoskeletons, and 18 other unique exoskeletons, illustrating both the size of the literature and the need for clearer benchmarking.[36]

5.3.5 Maturity and current deployment pattern

Industrial exoskeletons are widely studied in laboratory settings and short workplace pilots, but routine, shift-scale deployment remains uneven. The most mature segment is passive shoulder and back-support systems, mainly because they are simpler to operate and maintain and easier to integrate into workstations without adding major operational burden.[5]

The evidence base is large but difficult to compare across devices and tasks. An evidence-mapping review identified 139 eligible studies, covering 33 back exoskeletons, 25 shoulder exoskeletons, and 18 other unique systems, highlighting both growth and fragmentation in methods and reporting.[36] Outcomes depend strongly on task fit: reviews report clearer benefits in sustained postures and more variable results in dynamic workflows with frequent transitions or constrained movements, where interference is more likely.[10]

Lower-limb posture supports (wearable chairs and squat-assist systems) with intent-aware control remain less established in real workplaces, which helps explain why most deployments still favour passive assistance or simple adjustability.[33]

6. Technological Overview

This section summarises the main system elements that drive performance and deployability: mechanical design and fit, actuation and power, the human-device interface, sensing, control, safety, and usability. The same elements appear across domains, but their design trade-offs differ because clinics, daily mobility, and workplaces impose different constraints.
Table 2 summarises typical design choices for structure, actuation, interface, sensing, control, safety, and usability across rehabilitation, personal mobility, and industrial exoskeletons. The table highlights where the same technology category is implemented differently across domains because the operating context and success criteria are different.

Table 2. Technology stack comparison across domains (Section 6 overview)

System element	Rehabilitation exoskeletons	Personal mobility exoskeletons	Industrial exoskeletons
Mechanical design and ergonomics	Predominantly rigid lower-limb structures optimised for sagittal-plane gait repetition. Multi-DOF support beyond sagittal gait is less common; joint misalignment can create parasitic forces and discomfort. Weight is a major constraint but is not consistently reported.[1]	Range from rigid frames for high-demand tasks (stairs, transfers) to passive/quasi-passive and soft/hybrid systems for walking/running economy. Wearability is strict: total worn mass and mass placement strongly affect comfort and metabolic cost. Barrier tasks push torque requirements.[38]	Built around task families: shoulder supports, back supports, and lower-limb posture supports. Constraints include kinematic compatibility, fit over PPE, and comfort over shift-length wear.[33]
Actuation and power	Mostly electric motors with gear reduction to meet torque needs. High-ratio transmissions reduce backdrivability and increase reflected inertia. Battery autonomy is typically session-scale; pack mass becomes a barrier for longer or less supervised use.[44]	Passive/quasi-passive elastic elements; powered motors; proximal actuation with cable transmission to reduce distal mass; hydraulic/pneumatic in high-force concepts. Session-scale autonomy and transmission durability can limit daily use.[12]	Passive devices dominate deployments; active/semi-active add complexity. Off-task behaviour matters: devices should not increase metabolic cost or impede walking between stations.[10]
Human–device interface and comfort	Cuffs/straps must transmit large loads while avoiding pressure hot spots (pelvis and shank). Comfort and repeatable fit limit tolerance and delivered dose; pressure is often under-reported.[44]	Interface often sets usable assistance ceiling. Long-wear comfort, skin friction, and attachment stability are decisive. Fast don/doff and repeatable fit are required for daily feasibility.[4]	Comfort, heat, and fit drift over a shift are frequent adoption barriers. Shared-device fleets add hygiene/cleaning constraints.[19]
Sensing and perception	Common: encoders, IMUs, and contact/pressure for gait phase. Richer stacks may include interaction force/torque and EMG/EEG. Main issue is value-per-burden due to setup/calibration.[24]	Often minimal sensing (IMU, joint angle, foot contact). Some systems use biomechanics-aware sensing (plantar pressure + torque) to scale assistance. Robustness under non-steady gait is a key challenge.[25]	Many passive devices have little sensing; sensing is often added for evaluation. Active assistance research uses intent prediction with tight timing constraints. Operational sensing matters only if it yields stable KPIs with low burden.[43]
Control strategies and AI	Deterministic state machines and predictable assistance are common in deployed systems. Adaptive/intent-aware methods are researched but not dominant in routine practice; learning is mainly proposed for supervision/tuning.[8]	Controllers must handle transitions safely. Some control is mechanical (passive clutches/springs). Non-steady failure modes and user adaptation affect benefit.[28]	Control is often simple: passive torque–angle profiles; limited mode switching in active systems. Intent prediction is promising but field reliability is constrained by variability and drift; bounded adjustability is favoured.[33]

[44] Falkowski et al., 2024. Systematic review of mechanical designs of rehabilitation exoskeletons for lower-extremity. Archive of Mechanical Engineering, 71.

Safety mechanisms	Layered safety: mechanical stops, conservative torque/speed caps, supervision, and sometimes harness/BWS. Monitoring and hazard detection become more important outside controlled settings.[40]	Safety must hold under variability. Devices may include torque-off on snagging; balance recovery assistance is an emerging direction.[32]	Predictable fail-safe behaviour is required. Study-level safety reporting is inconsistent, complicating safety cases for large deployments.[33]
Usability and workflow fit	Clinic workflow is decisive: don/doff time, fitting steps, staffing, and reliability determine delivered dose. User and clinician adaptation effort affects tolerance.[15]	"Livability" dominates: comfort, noise, weight, maintenance, learning curve, and integration with routines and mobility aids. Users may request improvements even after successful trials.[18]	Workflow fit determines adoption: interference, don/doff time, and PPE clashes drive removal. Success depends on training, voluntary-use policies, maintenance, and task selection.[10]

6.1 Rehabilitation exoskeletons

6.1.1 Mechanical design and ergonomics

Most rehabilitation gait exoskeletons use rigid link structures that run in parallel with the leg and mainly support sagittal-plane hip and knee flexion–extension, with ankle assistance included in a subset of systems depending on the device architecture and clinical target. This design approach matches the dominant rehabilitation task: repeated stepping practice in straight-line walking, often delivered under controlled conditions. A large share of reported designs use three active degrees of freedom per leg (hip, knee, ankle), which supports repeated gait cycles and joint-level assistance but does not fully address multi-planar actions that become important as training moves toward more functional walking, such as turning, side stepping, and other tasks that require frontal- and transverse-plane hip motion and pelvis control.[44]

A persistent design challenge is joint alignment between the exoskeleton and the user. If the robot joint axis and the anatomical joint centre do not align well, the device can generate parasitic forces and unwanted shear at the interface, increasing discomfort and reducing tolerance, especially at the pelvis and shank where high forces are transmitted through cuffs, straps, and structural attachments. This is not a minor engineering detail, because discomfort and misfit directly affect clinical usability: they can lengthen fitting time, increase the need for repeated adjustments, and limit the dose that can be delivered within a session even if the control strategy is stable. Reviews of commercial and research systems repeatedly identify alignment and interface issues as central barriers to long-session comfort and routine deployment.[44]

Mass remains a major practical constraint, but reporting is inconsistent, which makes comparison and design learning harder. In one mechanical review, 63.46% of surveyed designs did not report device weight; among those that did, only 9.62% were ≤ 5 kg and 9.62% were > 15 kg, illustrating both wide variability and a basic reporting gap.[44] In practice, clinical services often manage the mass and stability challenge through supervised operation and external support, including harness-based systems in treadmill and hybrid configurations. This helps explain why treadmill-based and supported overground setups remain common in rehabilitation: they allow higher-dose stepping practice with a larger safety envelope even when the wearable system itself is heavy or not fully self-supporting.[44]

6.1.2 Actuation and power supply

Rehabilitation exoskeletons are predominantly electrically driven, and high-torque brushless DC motor plus gearbox combinations are common because they can deliver the joint torques needed to support stepping in impaired users across a range of gait speeds and assistance levels. The trade-off is that high-ratio transmissions increase reflected inertia and friction and reduce backdrivability, which can make the device feel less transparent during user-initiated movement and can complicate torque control when the goal is to allow natural variability rather than enforce a fixed trajectory. This is one reason many clinically deployed systems favour conservative assistance profiles and layered safety limits: when the actuator–transmission unit is stiff and not easily backdriven, it becomes more important to constrain torque and speed and to ensure predictable behaviour under disturbances or user mis-steps.[44]

Research systems explore alternatives intended to improve physical interaction through compliance, including compliant actuation (for example, series elastic elements), cable-driven architectures, and other approaches that can reduce peak contact forces and improve comfort by allowing controlled mechanical "give" at the joint. These approaches can improve interaction quality and may support safer assist-as-needed behaviour, but they also introduce integration burdens that matter in clinical deployment: cable routing and wear, added calibration and sensing requirements, increased packaging complexity, and maintenance demands that can reduce reliability and increase setup time.[24]

Battery and autonomy are typically adequate for supervised clinical sessions, where treatment is delivered in planned time blocks and the device can be charged and maintained between sessions. However, battery systems become more limiting as the use-case shifts toward longer sessions, higher duty cycles, or less supervised settings, because the battery pack adds mass and changes mass distribution and can directly affect donning/doffing time, comfort, and perceived burden.[23] In practice, "how long it runs" is only part of the issue; where the battery is carried and how it affects fitting and movement can become a primary barrier when the device is expected to be worn beyond controlled clinic workflows.

6.1.3 Human–device interface and comfort

The interface is where assistance becomes usable or unusable. In rehabilitation, cuffs, straps, harnesses, and padding must transmit large forces while limiting pressure hot spots and skin irritation. A practical clinical requirement is repeatable fitting: if pressure distribution changes between sessions, comfort and safety vary and users may not tolerate long or frequent sessions. A useful design target described in the rehab literature is that a "good" wearable robot should be safe, light, and easy to don and doff, and should rely on as few body attachments as possible while still being stable.[1] This is not an aesthetic preference; it reflects direct constraints on clinical throughput and the ability to deliver dose.

6.1.4 Sensing and perception

Rehabilitation systems typically use joint encoders and inertial measurement units (IMUs), often combined with foot-contact sensing, to estimate gait phase and support reliable state-based control. These sensors are practical because they are relatively robust, can be integrated into the device, and support repeatable operation across users.[40]

Richer sensing stacks are used when the goal is to measure interaction quality or to move toward more adaptive assistance. Common additions include plantar pressure sensing to capture stance dynamics and loading patterns, and interaction force/torque sensing to quantify how the user and device share effort. These signals can support features such as assistance scaling, detection of abnormal interaction patterns, and more detailed monitoring of training quality.[40]

Bio-signals such as surface EMG and EEG are used in some systems to estimate movement intention at the source, rather than inferring intent indirectly from kinematics and contact timing. This is most visible in intention recognition work and in BCI-triggered or BCI-modulated approaches. However, these signals introduce practical barriers in routine rehabilitation use: electrode placement, signal variability, sensitivity to noise and sweat, calibration time, and the need for reliable performance across sessions and across different users.[24]

Overall, the key sensing challenge is not sensor availability, but achieving a good value-to-burden balance. Sensors must provide information that improves safety, clinical usability, or personalisation without adding setup steps that reduce throughput or increase failure points in routine service delivery.

6.1.5 Control strategies and AI

Clinically deployed rehabilitation systems often rely on robust state-machine control and predictable assistance profiles, including fixed or semi-fixed trajectories, because these approaches are easier to verify, easier to certify, and easier for clinicians to use consistently across patients and sessions. In practice, they provide clear operating modes, stable transitions, and repeatable behaviour that fits supervised workflows and reduces the risk of unexpected device actions during gait training. This preference for predictable control is reinforced by the realities of clinical service delivery: staff must be able to set up the system quickly, apply standard protocols, and trust that the device will behave safely under common disturbances.[7]

Research increasingly targets assistance-as-needed strategies, impedance/admittance control, and intent-aware methods in which assistance adapts to user effort, gait phase, or interaction conditions rather than enforcing a single reference pattern. The motivation is clinical relevance: adaptive assistance is intended to support motor learning, reduce over-assistance, and better accommodate changes in capability across users and across sessions. However, systematic evidence indicates that adaptive strategies are still implemented in a minority of clinically reported devices, even though they are widely discussed as a key future direction. This gap reflects the difficulty of delivering robust adaptation under real user variability while maintaining interpretable behaviour that clinicians can manage and trust.[8]

Learning-based modules are often proposed to improve intention recognition, state estimation, and automated tuning of controller parameters, particularly where richer sensing (IMUs, pressure, interaction forces, EMG/EEG) can provide additional information about user intent.

The main barrier to translation is not proof-of-concept accuracy in controlled settings, but the need for deterministic safety behaviour and certifiable performance under noise, drift, and person-to-person differences. For clinical deployment, learning components must be bounded, transparent, and robust enough to avoid unstable or surprising assistance when conditions change, which is why many authors describe learning as most feasible in supervisory roles (tuning and monitoring) rather than as the primary torque-generation mechanism.[40]

6.1.6 Safety mechanisms

Safety in rehabilitation is achieved through layered measures that combine hardware constraints and supervised operation. At the device level, systems use mechanical joint limits and conservative torque and speed caps to reduce the risk of unsafe motion or excessive interaction forces, and many treadmill-based or hybrid configurations add harness-based body-weight support to provide fall protection and controlled exposure to stepping. In practice, safety is also procedural: trained staff supervise sessions, apply inclusion criteria, and manage progression so the user remains within a safe operating envelope. As use expands from steady treadmill cycles to more variable overground tasks and transitions, reviews and control-oriented reviews emphasise the need for multi-layer monitoring that can detect abnormal interaction patterns, mode-switching failures, loss of stability, or device faults early enough to trigger predictable safe responses rather than relying only on conservative limits.[45]

6.1.7 Usability, workflow fit, and user experience

Rehabilitation systems succeed when they fit routine clinical delivery, not only when they perform well in controlled testing. Practical factors such as donning/doffing time, the number of setup and calibration steps, and staffing requirements directly determine throughput, session efficiency, and whether the device can be used frequently enough to deliver meaningful training dose.[11] These workflow constraints also interact with user experience: learning to move with an exoskeleton often requires sustained effort from both the user and clinical staff, including coaching and repeated familiarisation, and tolerance can be limited by discomfort, fatigue, or the cognitive burden of coordinating movement with the device.[15] As a result, usability and workflow fit are closely tied to adherence and the likelihood that exoskeleton training becomes a reliable part of standard care rather than an occasional, high-effort intervention.

6.2 Personal mobility exoskeletons

6.2.1 Mechanical design and ergonomics

Personal mobility systems face stricter wearability constraints because the user must carry the system through daily movement and transitions. Designs range from rigid jointed frames

[45] Su et al., 2023. Review of adaptive control for stroke lower limb exoskeleton rehabilitation robot based on motion intention recognition. Frontiers in Neurorobotics, 17, 1186175.

for high-demand tasks (especially stairs) to passive or quasi-passive braces and soft or hybrid approaches for walking or running economy.[46]

Mass and mass placement are decisive. A review of (quasi-)passive lower-limb devices reports masses from 0.3 kg to 13.87 kg, with most systems below 3 kg, reflecting strong pressure toward lightweight designs in personal use.[38] For walking and running, studies explicitly note that mass placed away from the body's centre of gravity (especially distal mass) can increase metabolic cost and reduce comfort, which can erase the expected benefit.[21]

Concrete examples show the main design patterns:

- A community-oriented hip exoskeleton system (EX1) uses a waist-and-thigh architecture and reports 2.1 kg mass.[18]
- A running-focused hip system (HARE) concentrates mass around the waist/backpack area and reports 5.5 kg platform mass with two driven hip joints, explicitly aiming to reduce negative effects of distal mass during running.[17]
- A passive hip exoskeleton designed for both walking and running reports 1305 g total mass and includes a waist–thigh linkage that allows hip motion beyond pure flexion–extension (to reduce constraint).[38]

However, the design constraints tighten further when the device must support barrier tasks. Stairs require larger joint excursions and higher joint moments than level walking, so devices designed for stair assistance often need higher torque capacity even if that increases mass. Consistent with this, a powered knee exoskeleton for stair ascent reports a compact joint shell (30 mm thick, 60 mm wide), a leg segment weight of 2.9 kg (knee + thigh), and reported driving torques up to 180 Nm, illustrating how stairs shift the torque–mass trade-off.[25]

6.2.2 Actuation and power supply

Personal mobility devices cluster into four actuation approaches: passive/quasi-passive elastic elements, powered electric motors, powered systems with proximal actuation and cable transmission, and (less commonly in portable systems) hydraulic/pneumatic approaches when very high forces are targeted.[12]

Passive and quasi-passive designs store and return energy with minimal complexity and no batteries. A passive hip device reported net metabolic-rate reductions of 8.2% ± 1.5% (walking) and 9.1% ± 1.3% (running) at separately optimised stiffnesses, and 7.2% ± 1.2% (walking) and 6.9% ± 0.8% (running) using a common stiffness, showing that mechanical tuning can deliver multi-task benefit.[38] Another passive hip system reports 1.8 kg total mass and makes the stiffness tuning problem explicit.[27]

Powered devices aim for larger, more consistent assistance while staying portable. EX1 reports about 2 hours of continuous walking at 3 km/h and maximum noise below 60 dB at 1 m, illustrating that "home use" constraints include not only assistance but also autonomy and

[46] Chen et al., 2019. Knee exoskeletons for gait rehabilitation and human performance augmentation: A state-of-the-art. Mechanism and Machine Theory, 134, 499–511.

noise.[18] Proximal actuation and cable transmission are used to keep the ankle/foot light. One ankle exoskeleton reports that 300 N cable force with an 18 cm lever arm yields about 52 Nm ankle torque with 59% transmission efficiency (tested without a portable power source in that configuration), illustrating why designers try to move motors toward the waist while still delivering useful ankle torque.[4]

As assistance magnitude increases, transmission durability can become the limiting factor, especially in portable running systems that operate at high torque and high cycle counts. A powered ankle running exoskeleton using twisted-string transmission reports a minimum string lifespan of 3 min 22 s under 43 Nm peak torque assistance, requiring replacement between trials; this is a clear example of how a lightweight high-torque transmission can shift the bottleneck to component wear.[30] Some designs target burst-like actions rather than continuous gait-only support. A body-powered lower-extremity design reports spring torque capacity of 132 N·m, energy storage up to 126.7 J per actuator (over eight accumulation cycles), release within 110 ms, around 20.25 W to maintain a locked state, and peak actuation power around 3.46 kW during release.[42]

6.2.3 Human–device interface and comfort

In personal mobility, the interface often sets the usable assistance ceiling. Straps, braces, cuffs, and boots must transmit force without creating pressure hot spots, skin friction, or unstable attachment during dynamic movement.[4]

Designs respond in two main ways:

- Improve fit through orthotics-style shaping and adjustability to accommodate irregular body surfaces.[38]
- Route forces through structures (for example, strut-based interfaces) to reduce friction and manage load paths during walking.[4]

Donning and doffing time is a real usability requirement in personal systems. A knee-exoskeleton review reports a running-assist concept at 2.466 kg total mass with 30 s donning and 5 s doffing, illustrating what “daily feasible” can look like as a practical benchmark.[46]

6.2.4 Sensing and perception

Personal mobility devices often use minimal sensing because simplicity supports wearability, reliability, and fast setup in everyday use. Common configurations rely on IMUs and joint angle sensing to track limb motion, combined with simple foot-contact or in-shoe sensors to infer stance and swing and trigger phase-based assistance. This approach is practical for walking and running because it avoids heavy calibration and can be integrated into compact wearable hardware, but it can be less robust when the user moves outside steady patterns (for example, speed changes, uneven surfaces, stairs, or frequent stop–start transitions), where phase timing and contact signals can become less predictable.[18]

Some systems extend this minimal approach by using biomechanics-aware sensing so assistance is scaled to user demand rather than applied as a fixed profile. In one ankle exoskeleton study,[31] plantar pressure sensing was combined with a torque sensor, and the authors cite prior validation showing >90% accuracy for pressure-based estimation of biological ankle moment. Assistance and resistance were then defined as fractions of that estimated moment, which links sensing directly to the functional goal of "assist what the body is doing" rather than simply assisting at a fixed time in the gait cycle. This type of sensing can improve alignment between assistance magnitude and task demand, but it also increases requirements for signal stability and repeatability across footwear, fit, and real-world conditions, which is a central challenge for personal mobility deployment.

6.2.5 Control strategies and AI

Personal mobility controllers prioritise safe behaviour during transitions because daily mobility includes start–stop events, speed changes, turns, and barrier tasks, not just steady walking. Stair assistance, in particular, often relies on explicit gait-phase detection and state-based switching because the mechanical demands and timing differ between stance and swing and between level walking and stair ascent. A stair-ascent knee exoskeleton[25] illustrates this approach: it uses contact sensors to identify gait phases and applies different control strategies in stance and swing, with the stated goal of maintaining smooth transitions and stable switching so assistance does not create abrupt torque changes that could destabilise the user. In practice, this reflects a broader design requirement for personal mobility: controllers must manage task switching and phase transitions predictably, because "good average assistance" is not sufficient if the device behaves inconsistently at transitions.

In economy-focused systems, control can be mechanical rather than computational, especially in passive and quasi-passive designs where the goal is to influence joint energetics without motors or batteries. Classic passive knee concepts focus on providing stance-phase resistance or assistance while avoiding swing interference, which is a control problem solved through engagement mechanisms and timing logic embedded in the hardware (for example, clutches or switchable elements) rather than software alone.[32] This design philosophy highlights a core personal mobility constraint: assistance must be present when useful and absent when it would hinder natural motion. Clutch-based designs also show why non-steady gait is a critical test case. Undesirable locking during rapid deceleration is reported as a failure mode that can compromise safety, motivating explicit disable modes and conservative handling of transitions.[32] These findings underline that personal mobility control is as much about safe disengagement and predictable off-behaviour as it is about assistance magnitude.

User adaptation also interacts with control performance and perceived benefit. In older adults using ankle assistance, minimum metabolic power occurred around 6.6 ± 1.6 min in assistance mode and minimum soleus iEMG occurred around 6.0 min and was 17% lower than no-assistance.[31] This indicates that performance and comfort may stabilise only after several minutes of exposure, rather than immediately when assistance is turned on. For personal mobility deployment, this matters because users may judge the device during the first minutes of use, while the measurable physiological benefit may require a short familiarisation period; it also implies that controller tuning and feedback may need to support faster adaptation in real-world use.

6.2.6 Safety mechanisms

Personal mobility safety must hold under real-world variability, because users face speed changes, turns, uneven surfaces, and unexpected events that are less predictable than controlled lab walking. As a result, safety is typically implemented through a combination of hardware constraints and software responses that limit both the magnitude and the consequences of assistance when something goes wrong. Wearable systems designed for community use report mechanical stoppers and torque caps to prevent unsafe joint excursions or excessive assistance, and they also include explicit fault responses; for example, one hip exoskeleton reports a “torque-off” response when clothing is caught, paired with a warning through the associated application.[18]

Beyond these basic safeguards, some personal mobility research treats balance recovery as a primary safety function rather than an add-on. Balance assistance work describes an approach that detects instability and applies recovery assistance intended to help the user regain balance, reflecting the requirement that a personal mobility device must remain safe not only during steady gait but also during disturbances where falls are most likely to occur.[26]

6.2.7 Usability, UX, and acceptance

Personal mobility adoption depends on “livability,” meaning the device must be acceptable in daily routines, not only effective during short, supervised tests. Even when trials are safe and show measurable benefits, users may still request improvements in weight, noise, and design because those factors often determine whether the device will be worn routinely rather than occasionally. For example, in a randomised trial in older adults using a hip exoskeleton, participants completed the protocol safely but still suggested improvements to weight, noise, and design, practical issues that directly affect long-wear willingness and social acceptability.[18]

Qualitative evidence in older adults and caregivers reinforces that acceptance is not automatic: it emphasises a progressive learning process and highlights that exoskeletons can be perceived as stressful or “futuristic,” with some users preferring familiar aids (such as canes or wheelchairs) if the device feels burdensome or difficult to master. These findings indicate that adoption depends on both physical usability (comfort, don/doff, noise, maintenance) and psychosocial fit (confidence, dignity, and perceived normality), and that support and training are often part of making a personal mobility system usable in practice.[16]

6.3 Industrial exoskeletons

6.3.1 Mechanical design and ergonomics

Industrial exoskeletons are designed around specific task families: overhead work (shoulder/upper-limb), manual handling and trunk flexion (back support), and sustained awkward postures (lower-limb posture supports).[5]

For upper-limb devices, mechanism design aims to provide helpful torque during arm elevation while preserving workspace and avoiding interference with natural shoulder motion and tool use. A shoulder-support review reports that assistance is often elevation-dependent and can peak around 70–110° shoulder flexion, which aligns with the posture range where many overhead tasks accumulate shoulder load during sustained or repetitive work.[33] Because workers still need reach, cross-body motion, and access to tight spaces, the mechanism must support the arm without blocking the workspace or forcing awkward compensations. Mechanism families such as double-parallelogram and scissor-like structures are used to preserve workspace while keeping link masses close to the body and routing reaction forces to load-bearing regions (typically the torso/hips), which is intended to reduce perceived bulk and improve comfort during extended wear.[47]

For back and trunk systems, the frame routes load from the trunk to the pelvis and thighs or other load-bearing regions to reduce demand during lifting and forward bending. In practice, these systems must balance assistance with mobility: workers still need to walk, turn, climb, and handle loads with variable posture, so designs that support flexion can also risk restricting range of motion or creating unwanted forces during non-target movements. Fit and load path choices directly affect comfort and acceptance because pressures are concentrated around the pelvis, chest, and thigh interfaces; small mismatches or strap creep across a shift can create pressure hot spots, skin irritation, and long-shift discomfort that can lead to non-use even when biomechanical benefits are measured.[37]

For lower-limb posture supports, wearable chairs and squat-assist devices transfer body load toward the ground through shank/foot interfaces and aim to stabilise low postures during prolonged squatting or kneeling. The core usability challenge is that these devices must support the target posture while still allowing safe transitions (entering and leaving the supported mode, walking between stations, and maintaining balance on uneven or cluttered surfaces). A review[34] reports large plantar-pressure offloading in supported postures and large reductions in muscular demand, indicating strong potential for reducing local fatigue, but it also highlights discomfort and “unsafe feeling” as barriers, reinforcing that perceived stability and comfort during transitions are as important as the magnitude of offloading in the supported posture itself.

6.3.2 Actuation and power supply

Passive designs dominate industrial deployments because they are typically lighter, quieter, and simpler to operate than powered systems, and they avoid charging infrastructure and battery-related downtime. This is especially true for shoulder supports used on production lines, where devices must be worn for long periods, shared across workers, and integrated into routine workflow without adding complex maintenance requirements. In practice, passive systems also reduce organisational barriers because they can be deployed with fewer changes to work processes and fewer failure modes related to power management.[10]

At the same time, the industrial back-support design space is broader and includes passive, active, and quasi-passive systems, reflecting the wide range of tasks and postures in manual handling and forward bending. One review explicitly frames lumbar devices as powered, unpowered, and quasi-passive and notes that evaluation methods are not yet unified, which

[47] Tian et al., 2024 (December). A systematic review of occupational shoulder exoskeletons for industrial use: mechanism design, actuators, control, and evaluation aspects. Actuators, 13(12), 501.

limits comparison across systems and makes procurement decisions harder.[48] A broader back-support review that includes exosuits and rigid systems highlights that adoption remains constrained by technical challenges and the lack of established safety standards and guidance for field use, reinforcing that powered assistance alone does not guarantee deployability.[14]

Lower-limb posture supports (wearable chairs and squat-assist systems) can include semi-active variants intended to adjust assistance level across postures or stations. A key operational issue is that industrial systems are worn across mixed tasks: workers need to walk between stations and change posture frequently, so any added assistance must not impose excessive metabolic or movement penalties during non-target activities. This is why “off-task” behaviour (how the system feels and behaves while walking or transitioning) can be as important for real adoption as the measured benefit in the supported posture itself.[34]

6.3.3 Human–device interface and comfort

Industrial interfaces must work under shift-length wear, sweat and heat, and in combination with personal protective equipment (PPE), while still allowing full job-relevant range of motion. Comfort is therefore often the limiting factor in real deployment: even when studies report reductions in muscle activity, poor pressure distribution, strap creep, heat build-up, or rubbing at load-bearing contact points can lead workers to remove the device or avoid using it. Acceptance-focused reviews emphasise that comfort, perceived restriction, and ease of donning/doffing strongly influence whether workers will adopt the system consistently in daily work rather than only during short trials.[19]

Because industrial deployment often involves shared devices, hygiene and cleaning workflows also matter as practical adoption requirements. Pads, straps, and contact interfaces must be easy to clean or replace, and fit must remain stable across a shift as clothing layers change, straps loosen with movement, and users cycle through different postures. Field-oriented work highlights that these “small” interface issues can dominate user experience over time, affecting willingness to wear the device even when biomechanical endpoints look positive in controlled tasks.[10]

6.3.4 Sensing and perception

Many deployed passive industrial devices have minimal sensing, because sensing adds cost, maintenance, and potential failure points and is not always necessary to deliver passive assistance. In research settings, sensing is often added primarily for evaluation (especially EMG and kinematic measures) to quantify changes in physical demand during controlled tasks. In the workplace, however, sensing adds value only if it produces operationally useful information without adding burden for workers or supervisors. Evidence-mapping work shows that studies use a wide range of metrics, tasks, and postures, reflecting limited standardisation and making it difficult to translate “measured effects” into simple indicators that organisations can track over time.[36]

[48] Qu et al., 2025. A Review of Wearable Back-Support Exoskeletons for Preventing Work-Related Musculoskeletal Disorders. Biomimetics, 10(5), 337.

Active upper-limb industrial exoskeleton research explores intention prediction to align assistance timing with the user's movement and task phase. A systematic review[43] includes 29 studies and reports that many approaches rely on motion capture and EMG, with prediction windows ranging from about 450 ms before to 660 ms after motion onset. These findings underline a practical constraint: intent must be detected early and reliably enough to deliver assistance at the right time, despite workflow variability and differences across workers, tools, and stations.

6.3.5 Control strategies and AI

Industrial control often stays simple for reliability and predictability under field conditions. Passive devices implement assistance through fixed mechanical torque–angle profiles that deliver support in the target posture range without sensors or computation. Active devices can shape assistance using motors and sensing, but robust intent detection in real work is difficult because workflows are variable, tasks are mixed, and calibration can drift across a shift due to sweat, clothing, and strap movement. As a result, many field-ready concepts prioritise predictable behaviour and clear "off" characteristics rather than maximising assistance authority.[33]

Where adaptive control is proposed, practical industrial design tends to favour semi-active or adjustable assistance that can be tuned per station or task family without high operational burden. This approach aims to keep the simplicity and reliability advantages of passive systems while allowing limited adjustment to match different tool weights or posture ranges, rather than relying on complex black-box behaviour that is harder to validate and harder for workers to trust.[33]

6.3.6 Safety mechanisms

Industrial safety requires predictable fail-safe behaviour under realistic work conditions: safe default behaviour on power loss, avoidance of unintended torque injection, and reduced entrapment risk during overhead work and tool handling.[33] In practice, safety also includes how the device behaves during transitions and non-target movements, because workers do not stay in the assisted posture continuously. Methodology reviews highlight that safety aspects are not consistently addressed in studies and that evaluation approaches are not standardised, which limits how confidently safety cases can be built from the published literature alone and reinforces the need for structured, task-representative field validation.[35]

6.3.7 Usability, workflow fit, and deployment reality

Industrial adoption depends on task fit and workflow fit, not only on biomechanical effect in a single posture. In practice, reviews report clearer benefit in more static tasks and more variable outcomes in dynamic sequences where interference is more likely, such as mixed reaching, frequent walking between stations, or constrained spaces that require unrestricted trunk or shoulder motion.[10] Adoption also depends on worker acceptance factors (comfort, ease of use, learnability) and organisational factors (training, voluntariness, maintenance planning, and integration into ergonomics and safety processes), because these determine whether the device is worn consistently over time.[19]

A useful reality check is the size and heterogeneity of the evidence base: an evidence-mapping review[36] identified 139 eligible studies covering 33 back exoskeletons, 25 shoulder exoskeletons, and 18 other unique systems. This breadth shows strong activity, but it also highlights why standardised evaluation remains a core need for procurement and scale-up: without comparable tasks, metrics, and reporting, it is difficult to translate pilot outcomes into confident deployment decisions across sites and worker populations.

7. Clinical and Operational Validation

This section summarises validation evidence in rehabilitation, personal mobility, and industrial use. It separates clinical validation (safety and measurable benefit) from operational validation (setup burden, training requirements, workflow fit, adherence, and failure modes). Evidence limitations are stated explicitly where follow-up, duration, or field realism are limited.

Table 3 lists common endpoints used across domains and summarises what each endpoint is used to represent in context..

Table 3. Outcome and endpoint mapping across domains

Outcome family	Typical metrics used	What it indicates (plain meaning)	Most common domain(s)	Key limitations / interpretation notes	Evidence literature
Functional walking capacity	10MWT, 6MWT/2MWT, TUG, gait speed, step length, cadence	Whether the user can walk faster/further and perform basic functional walking tasks	Rehabilitation; Personal mobility (older adults)	Affected by protocol differences and supervision; treadmill vs overground context matters	(de Miguel-Fernández et al., 2023;[8] Plaza et al., 2021;[1] Jayaraman et al., 2022;[2] Lee et al., 2022)[18]
Mobility-related independence	FIM, Barthel Index, SCIM, WISCI-II, FAC	Whether walking and daily mobility require less assistance or fewer aids	Rehabilitation	Cross-study comparison is limited by heterogeneous inclusion criteria and dose	(de Miguel-Fernández et al., 2023;[8] Plaza et al., 2021;[1] Gupta et al., 2023)[22]
Balance and stability (clinical/functional)	BBS, FGA	Balance function relevant to community mobility and fall risk	Personal mobility; Rehabilitation (some studies)	Balance scales are not the same as real-world falls; fall outcomes often not directly measured	(de Miguel-Fernández et al., 2023;[8] Jayaraman et al., 2022)[2]
Biomechanics: kinematics	Joint angles/ROM (hip/knee/ankle), gait kinematics	How movement pattern changes (mechanistic insight)	Rehabilitation; Personal mobility (barrier tasks)	Less consistently reported than clinical scales; lab instrumentation may limit field transfer	(de Miguel-Fernández et al., 2023;[8] Zhang et al., 2021)[50]
Biomechanics: kinetics / joint demand	Joint moments/torques; task-specific mechanical requirements	How much mechanical support is required (engineering realism)	Personal mobility (stairs/loads)	Values are task/load dependent; not direct measures of independence	(Zhang et al., 2021;[50] Bougrinat et al., 2019)[4]
Physiology: energy expenditure / economy	Net metabolic cost/power; oxygen consumption; cost of transport	Whether the device reduces effort during walking/running (fatigue relevance)	Personal mobility; Rehabilitation (less common)	Benefit depends on tuning and adaptation time; short exposures can underestimate benefit	(Zhou et al., 2024;[9] Sawicki et al., 2020;[12] Fang et al., 2022;[31] de Miguel-Fernández et al., 2023)[8]

Muscle activity / neuromuscular response	EMG/sEMG; iEMG	Whether muscular demand changes and whether patterns adapt over exposure	Rehabilitation; Personal mobility; Industrial	EMG is task- and placement-dependent; target-muscle changes do not prove whole-body risk reduction	(de Miguel-Fernández et al., 2023;[8] Fang et al., 2022;[31] De Bock et al., 2022;[36] Ali et al., 2021)[14]
Neural measures / intent from CNS	EEG/BCI-triggered or modulated walking; neural activity measures	Whether neural signals can be used to trigger/shape assistance (experimental direction)	Rehabilitation (experimental)	Evidence remains experimental; operational robustness is a barrier	(Colucci et al., 2022;[39] de Miguel-Fernández et al., 2023)[8]
Exposure proxies (workload and posture at work)	EMG, posture/kinematics, sometimes heart rate; task time	Whether physical exposure during a work task is reduced	Industrial	Lab-to-field gap is common; exposure reduction ≠ proven injury prevention	(Bar et al., 2021;[3] De Bock et al., 2022;[36] Baldassarre et al., 2022)[10]
User experience and acceptance	Perceived exertion, discomfort ratings, usability; QUEST	Whether users tolerate and want to continue using the device	Personal mobility; Industrial; also rehabilitation (complementary)	Often under-standardised; changes with learning and support; decisive for adoption	(Jayaraman et al., 2022;[2] Lee et al., 2022;[18] Andrade et al., 2022;[19] De Bock et al., 2022;[36] del Rio Carral et al., 2022)[16]
Safety and adverse events / incidents	Adverse events, falls (where reported), device malfunctions, “unsafe feeling” reports	Whether use can be delivered without unacceptable harm or incidents	All domains	Reporting inconsistent; supervised safety ≠ unsupervised daily safety	(Jayaraman et al., 2022;[2] Gupta et al., 2022;[22] Hoffmann et al., 2022;[35] Kuber et al., 2023)[34]
Operational feasibility / workflow fit	Don/doff time, setup burden, staffing needs, maintenance, interference with task cycles	Whether the device can be used routinely in the real setting	All domains	Often described qualitatively rather than with standard metrics; drives uptake	(Plaza et al., 2021;[1] Plaza et al., 2023;[11] Lee et al., 2022;[18] Andrade et al., 2022;[19] Crea et al., 2021)[6]

7.1 Rehabilitation exoskeletons

7.1.1 Study types and evidence maturity

Rehabilitation exoskeleton evidence includes device-specific clinical trials and broader reviews across many systems. The overall evidence base is large but uneven in quality and design rigor. In a systematic review[8] focused on powered lower-limb exoskeletons after brain injury, most studies were observational (66.04%), while controlled trials represented 10.06% and randomised controlled trials represented 22.64%. Only 12.58% of studies included follow-up, which was typically around 4 months after the final intervention. These numbers matter because they define what can be concluded: feasibility and short-term change are commonly reported, but long-term durability of benefit is less well established.

At the device level, the published clinical evidence is concentrated in a relatively small set of commercial or near-commercial rehabilitation exoskeletons that have been evaluated repeatedly in supervised programmes and reported with functional outcomes. In parallel, there is a much larger research pipeline of prototype systems that introduce new mechanical designs and control concepts but are tested in smaller studies, often with limited clinical cohorts and shorter validation pathways. As a result, the overall literature contains many device concepts, but the strongest and most repeatable clinical evidence is associated with a smaller number of widely deployed systems.[11]

7.1.2 Typical endpoints and what they show

Rehabilitation trials primarily use functional gait and mobility outcomes and independence measures, because these reflect real walking capacity and clinical goals. In the brain-injury exoskeleton evidence base, gait speed was reported in 37.74% of studies; cadence in 25.16% and step length in 23.27%. Frequently used clinical outcomes included 10MWT (20.75%), 6MWT (16.98%), TUG (10.06%), FAC (29.56%), BBS (14.47%), FIM (8.81%), and Barthel Index (11.32%).[8] These outcomes often show improvement in selected users under supervised training, but cross-study comparison is limited by variability in training dose, inclusion criteria, and outcome selection.

Biomechanical and physiological outcomes are reported less consistently than functional tests. In the reviewed evidence base, joint kinematics were reported in 44.65% of studies, energy expenditure in 10.69%, and neural activity measures in about 6.29%, which aligns with the practical reality that standard clinical mobility tests are easier to implement and compare across sites than instrumented biomechanics or neurophysiology.[11] Mechanism and adaptation measures are sometimes added to complement functional outcomes and to interpret how exoskeleton-assisted walking affects neuromuscular behaviour. Surface EMG was reported in 20.75% of studies and was used to characterise muscle activation patterns during exoskeleton-assisted walking and how they change across training or assistance conditions.[11]

7.1.3 Safety and adverse events

In supervised rehabilitation delivery, safety is supported by trained staff, controlled clinical environments, and—depending on the setup—body-weight support or external safety systems that reduce fall risk during stepping practice. Within this model, reviews generally describe exoskeleton-assisted gait training as feasible and safe when delivered under appropriate inclusion criteria, with staff training and supervision treated as part of the safety system rather than an optional add-on.[1]

Operational safety also depends on device reliability and how faults are handled in real sessions. In an overground training programme in incomplete spinal cord injury, training was reported as feasible and safe, but device malfunctions occurred and required engineering support. This illustrates that "safety" in clinical practice includes not only adverse events in the user, but also predictable fault behaviour, rapid recovery from malfunctions, and the availability of technical support so that sessions can be completed without compromising safety or workflow.[22]

7.1.4 Operational feasibility and workflow fit

Operational feasibility in rehabilitation is defined by clinical throughput and repeatability across many users and many session days. Recurring constraints include fitting time, donning/doffing complexity, calibration steps, and the ability of staff to run the system reliably across different patient profiles without excessive adjustment or troubleshooting. These practical factors influence whether a device can be used frequently enough to deliver meaningful training dose.[11]

A second operational issue is standardisation across programmes and studies. The evidence base shows that no single outcome measure is used in more than half of studies, reflecting both diverse clinical aims and the absence of widely adopted standard protocols. This makes it difficult for services to compare programmes and limits the ability to attribute differences in outcomes to specific device features or control strategies.[8]

A third issue is user adaptation and tolerance. Human factors work describes that learning to use an exoskeleton often requires sustained effort by both the user and clinicians, and that this ongoing "body work" can shape comfort, confidence, and willingness to continue training. As a result, adherence and delivered dose depend not only on device performance but also on how demanding the learning and fitting process feels over repeated sessions.[15]

7.1.5 Evidence limitations and what is missing

The main limitations are limited follow-up, protocol heterogeneity, and inconsistent reporting, which restrict direct device-to-device comparisons and limit strong conclusions about which approaches work best for which users.[8] A practical gap is that many studies report functional outcomes without using device logs and sensing to explain mechanisms, quantify delivered dose in a consistent way, or support personalisation of assistance and progression. This limits cumulative learning across trials and slows translation from research findings to repeatable clinical implementation.[40]

7.2 Personal mobility exoskeletons

7.2.1 Study types and evidence maturity

Personal mobility validation spans three main study types: controlled laboratory studies that quantify locomotion economy (most commonly changes in metabolic cost during walking or running), device-specific experiments that focus on barrier tasks such as stairs, inclines, or sit-to-stand transitions where mechanical demands are higher, and a smaller set of community-delivered programmes (particularly in older adults) that test feasibility and functional outcomes in more realistic environments. This pattern reflects the state of maturity in the field: laboratory studies can isolate assistance effects under controlled conditions, while community programmes begin to address whether benefits translate to everyday mobility demands.[12]

In older adults, a systematic review identified 36 studies on wearable lower-limb exoskeletons/exosuits, indicating a growing evidence base, but one that remains heterogeneous in devices, protocols, and endpoints and is still mostly based on supervised or time-limited evaluations rather than long-duration daily-use deployment.[29] As a result, the literature supports short-term feasibility and measurable effects in defined tasks, while evidence on sustained adherence, routine home use, and longer-term functional impact remains comparatively limited.

7.2.2 Typical endpoints and what they show

Personal mobility evidence reports two main outcome families: functional mobility outcomes and locomotion economy outcomes.

Functional mobility and balance outcomes are most clearly represented in older-adult programmes and trials that use standard clinical tests and user satisfaction measures. In a community-delivered programme[2] in a senior living facility, participants completed 12 sessions (30 minutes per session over 4–6 weeks) and the study reported improvements in 10MWT (+0.18 m/s and +0.21 m/s), 6MWT (+62.5 m), BBS (+4 points), FGA (+5.1 points), and high satisfaction on QUEST (4.5 ± 0.6), with no reported adverse events and no device-related falls. In community-dwelling older adults using a hip exoskeleton (EX1), outcomes included improvements in gait performance and reductions in net metabolic energy cost during daily barrier tasks, 12.80% during stair ascent and 21.66% during incline walking under assistance mode, showing that personal systems can target tasks where demand is higher than level walking.[18] Longer training exposure has also been reported to matter: a hip-exoskeleton programme in older adults reported reduced metabolic cost of transport after 4 weeks, supporting that benefits can extend beyond a single-session demonstration when training is structured.[49]

Locomotion economy outcomes are most often quantified as changes in net metabolic cost during walking or running under controlled protocols, and reviews summarise that measurable reductions are achievable when devices are tuned appropriately. A quasi-passive review screened 203 papers (2014–2024) and retained 22 publications; across included studies it reports net metabolic cost reductions of 3.3–8.6% for walking and 4.0–8.0% for running.[9] A separate review identified 23 studies (through December 2019) that reported statistically improved walking and/or running economy compared with no device.[12] Device-level results illustrate both the scale of effect and the importance of tuning: an unpowered hip exoskeleton reported net metabolic-rate reductions of 8.2% ± 1.5% (walking) and 9.1% ± 1.3% (running) at separately optimised stiffnesses, and 7.2% ± 1.2% (walking) and 6.9% ± 0.8% (running) using a common stiffness.[9] A passive running-focused hip device reported an 8.0% ± 1.5% reduction in metabolic cost, and 10.2% ± 1.5% when device mass was included in normalisation.[27]

[49] Martini et al., 2019. Gait training using a robotic hip exoskeleton improves metabolic gait efficiency in the elderly. Scientific Reports, 9(1), 7157.

7.2.3 Safety and adverse events

Community-based programmes provide the clearest published evidence for safe delivery under realistic mobility tasks, but they are still typically supervised and time-limited. In the senior-living programme, the intervention was delivered without reported adverse events and without device-related falls, supporting feasibility and short-term safety when training is structured and monitored.[2] At the same time, most personal mobility studies remain short and supervised, which means the evidence base is still limited for long-term, unsupervised daily use, especially for safety during mixed-task mobility and unexpected events outside controlled sessions.[29]

7.2.4 Operational feasibility and workflow fit

Operational feasibility in personal mobility is defined by whether the device is practical to wear repeatedly in daily routines. Key requirements include fast donning/doffing, comfort over longer wear, stable performance during transitions, and durability that supports repeated use without frequent maintenance. Even when users complete protocols safely, they may still request improvements in weight, noise, and design, indicating that feasibility in a supervised trial does not automatically translate into routine daily wear.[18]

A second operational issue is user learning and acceptance. Qualitative evidence in older adults and caregivers describes a gradual learning process and highlights that exoskeletons may be perceived as stressful or “futuristic,” with concerns about mastering the technology and preference for familiar mobility aids in some cases.[16] These factors directly affect willingness to adopt the device outside supervised settings and reinforce that training and user support can be part of real-world feasibility.

A third operational constraint is serviceability. Some high-performance portable transmissions can require very frequent maintenance. For example, a twisted-string ankle exoskeleton reported a minimum string lifespan of 3 min 22 s under 43 Nm peak torque assistance, requiring replacement between trials.[30] This illustrates that durability and service intervals can become the limiting factor for repeated real-world use, even when assistance magnitude is achievable in controlled experiments.

7.2.5 Evidence limitations and what is missing

The biggest gap is long-duration, real-world daily-use evidence. Much of the literature is based on short-term trials, controlled protocols, or supervised programmes, which limits conclusions about adherence, sustained independence, and quality-of-life impact under routine use.[29] Another gap is evaluation under real variability (turns, speed changes, mixed tasks, and non-steady events) beyond steady treadmill or corridor walking. These conditions can change both safety and perceived benefit and are central to whether personal mobility devices will be accepted and used consistently.[32]

7.3 Industrial exoskeletons

7.3.1 Study types and evidence maturity

Industrial validation spans laboratory experiments, short workplace pilots, and reviews that catalogue devices, tasks, and outcome measures across the field. Evidence mapping illustrates the scale and heterogeneity of the literature: 139 eligible studies covering 33 back exoskeletons, 25 shoulder exoskeletons, and 18 other unique systems.[35] This breadth reflects strong research activity, but it also explains why consistent benchmarking remains difficult: studies differ in task selection, posture definitions, measurement sets, exposure duration, participant characteristics, and reporting quality, which limits direct comparison across devices and across sectors.

Roadmap work argues that moving from pilots to sustained use requires field validation in real work contexts with experienced workers and realistic workflows, rather than relying mainly on controlled tasks or brief trials. It also emphasises that the evidence collected must be usable for organisational decision-making, meaning it should support risk assessment approaches and workplace guidance (task selection, training, maintenance, and monitoring), not only demonstrate short-term reductions in physical demand under simplified conditions.[6]

7.3.2 Typical endpoints and what they show

Industrial studies most often rely on two types of outcomes: physiological and biomechanical indicators of how physical demands change during a task, and user experience measures that capture whether the device is tolerable and usable in practice. EMG and posture/kinematics are widely used to quantify changes in physical demand during targeted tasks, while perceived exertion, discomfort, and usability measures are used to capture acceptance and practical tolerance over the tested period.

Meta-analytic evidence supports short-term reductions in physical stress/strain in the body region supported by the exoskeleton, but it does not establish long-term prevention impact because long-duration field studies and injury outcomes are rarely measured.[3] For lower-limb industrial posture supports, a review of 23 articles reports large reductions in muscular demand (roughly 30–90%) and plantar-pressure reductions of about 54–80% in supported postures, alongside reported discomfort and “unsafe feeling” as barriers; it also reports reductions in low-back demands around 37%, showing that posture supports can shift load patterns in ways that may influence both comfort and perceived safety.[34] Workplace performance outcomes are strongly context dependent: reviews report clearer benefits in more static task segments and more variable results in dynamic workflows, where interference with movement, reach, or tool use can reduce net value.[10]

7.3.3 Safety and adverse events

Safety reporting in industrial exoskeleton studies is uneven. Methodology reviews note that safety aspects are not addressed consistently and that evaluation approaches are not standardised, which limits confidence about side effects and longer-term risk when moving from short trials to shift-scale use.[35] Meta-analytic work also highlights the need to consider effects beyond the assisted region, because assistance at one joint or body segment can shift loads, muscle activity, or posture demands to non-target regions, creating potential compensations that are not captured if evaluation focuses narrowly on the intended area of support.[3]

7.3.4 Operational feasibility and workflow fit

Operational feasibility in industry is defined by whether the device fits the work system and is worn consistently under real job conditions. Worker acceptance depends on discomfort, ease of use, learnability, and the conditions of use (for example, whether wearing is voluntary or mandated, the quality of training, and whether the perceived benefit outweighs inconvenience). Workplace studies also show that task mismatch can drive intermittent use or removal: if a device provides benefit only in a narrow posture range but the job includes frequent transitions, walking between stations, or tasks outside the assistance envelope, workers may remove the device during non-target tasks, reducing real exposure benefit over the shift.[10]

From a deployment perspective, evaluation must be structured to support decisions rather than only demonstrate effect in a simplified task. Roadmap work emphasises that field studies should be designed to capture workflow impact, tolerance over realistic wear durations, and side effects, and to produce evidence that can inform risk assessment and workplace guidance.[6] Multi-dimensional evaluation frameworks that combine metrics, tasks, and postures are therefore proposed to reduce the lab-to-field gap and improve comparability across devices and settings.[37]

7.3.5 Evidence limitations and what is missing

The main gaps are long-duration field evidence, standardised evaluation methods, and representative participant samples that reflect real worker populations and job demands.[6] Long-term prevention outcomes remain uncertain, and side effects and compensations in non-target regions are under-measured in many studies, limiting confidence about net benefit over months of use.[35] These gaps are particularly important because industrial adoption decisions depend on sustained, shift-scale usability and safety in real workflows, not only short-term laboratory effects or single-station demonstrations.

8. Technology Gap Analysis and Opportunity Mapping

This section summarises the main gaps that limit performance and adoption and maps practical opportunities to address them. Gaps are organised by domain, followed by a cross-domain summary that captures recurring issues that affect real deployment.

8.1 Rehabilitation exoskeletons

8.1.1 Mechanical design and ergonomics

Gap: most rehabilitation gait exoskeletons are built around sagittal-plane joint assistance and repetitive stepping, which fits treadmill practice and straight overground walking but does not directly support many functional actions (turning, side stepping, variable foot placement) that matter for real mobility. The mechanical design literature shows that three active degrees of freedom at the hip, knee, and ankle per limb are the most common configuration (34.6%), while systems with four or more degrees of freedom are relatively rare (about 13.5%).[44]
Opportunity: expand functional mobility without adding unnecessary weight. The goal is not to add more joints to every device, but to use modular designs so extra movement options are only added when they are needed. For example, the system could add a module that allows more hip side-to-side motion or better self-alignment when training targets turning or side stepping, while keeping a simpler, lighter setup for early straight-line stepping practice.

Gap: joint misalignment remains a real limiter. Misalignment between the exoskeleton joint and anatomical joint centres can create unwanted forces that reduce comfort and tolerance and increase setup burden. This issue is repeatedly linked to interfaces at the pelvis and shank and is not solved by control tuning alone.
Opportunity: make alignment compensation a standard design feature. Use passive self-alignment stages or self-aligning joints so the device can better match the user's joint motion and reduce unwanted forces. Describe these alignment features clearly in device specifications and in the clinical fitting procedure so they can be applied consistently in practice.

Gap: weight is a basic feasibility parameter, but it is often missing. In one mechanical review, 63.46% of surveyed designs did not report device weight; among those that did, only 9.62% were ≤ 5 kg and 9.62% were > 15 kg, making comparison difficult and limiting design-to-validation learning.[44]
Opportunity: report weight (and where mass is located), supported user size ranges, and donning/doffing time consistently to support clinical procurement and cross-study comparison.

8.1.2 Actuation and power supply

Gap: high-torque electric actuation with high-ratio transmissions is common and can deliver stepping assistance, but the trade-off is reduced backdrivability and increased reflected inertia. This pushes designs toward conservative control and safety limits and can reduce natural interaction.
Opportunity: design around torque bandwidth and backdrivability, not peak torque alone. Rehabilitation devices need predictable, controllable torque output and safe physical interaction under variability. Practical opportunities include actuator/transmission choices that improve backdrivability and interaction transparency while still meeting torque demands.

Gap: battery mass and placement become barriers when use moves beyond supervised sessions. Battery systems are generally sufficient for supervised sessions, but battery mass and placement become more limiting as the goal shifts toward longer use and less controlled environments.
Opportunity: use swappable battery packs and place battery mass close to the body's centre of mass to reduce perceived burden while supporting predictable session planning.

8.1.3 Human–device interface and comfort

Gap: many studies report functional outcomes without quantifying interface pressure distribution or long-session tolerance, even though discomfort can limit wear time and delivered dose.
Opportunity: measure and report interface tolerance as an engineering endpoint. Treat pressure hot spots, skin tolerance, and fit repeatability as core specifications and include them in validation, not only as narrative comments.

8.1.4 Sensing and perception

Gap: many systems rely on encoders, IMUs, and foot-contact sensing, while richer sensing (interaction forces, plantar pressure, EMG/EEG) is more common in prototypes.[24] The barrier is not sensor availability; it is robust use without adding setup time, calibration burden, and new failure modes.
Opportunity: use sensing that is simple but still useful. Combine a small set of reliable sensors (such as joint encoders, a limited number of IMUs, and selected interaction or load sensors) so the system provides information that matters without heavy setup and calibration. Use the sensor outputs directly for clinical decisions such as progression rules, assistance tuning, and safety monitoring.

8.1.5 Control strategies and AI

Gap: adaptive assistance is widely discussed but not dominant in clinically reported systems. The evidence base still contains many state-machine and fixed or semi-fixed trajectory approaches because they are robust and easier to validate. Adaptive strategies appear in a minority of devices in the clinical literature.[8]
Opportunity: keep the safety-critical loop deterministic (clear state machines and transitions), while adding adaptation through bounded, interpretable parameters (for example, state-dependent impedance tuning or assistance-as-needed scaling).

Gap: learning-based modules can support intention recognition or tuning, but translation is limited by certification needs and the challenge of robust performance under user variability and drift.
Opportunity: use learning for parameter tuning, drift detection, and hazard prediction while keeping direct torque control deterministic and auditable.

8.1.6 Safety mechanisms

Gap: safety is often environment-dependent. In clinics, safety is supported by supervision and, in some configurations, harness or external support. Moving toward less supervised environments raises safety requirements for transitions and unexpected events.
Opportunity: define and validate operating envelopes by user group. Specify safe envelopes (speed ranges, assistance limits, allowed transitions) and validate them for impairment groups rather than assuming one envelope fits all.

8.1.7 Usability and workflow fit

Gap: workflow burden limits dose delivery. Donning/doffing time, fitting complexity, staffing requirements, and maintenance shape whether the device is used frequently enough to matter.
Opportunity: reduce the number of steps required per session, simplify calibration, and design interfaces that preserve consistent fit across repeated sessions.

8.1.8 Evidence and validation gaps

Gap: evidence maturity is uneven and follow-up is limited. In one systematic review, 66.04% of studies were observational, 10.06% were controlled trials, and 22.64% were randomised controlled trials; only 12.58% included follow-up (typically ~4 months).[8]
Opportunity: standardise protocol reporting and use device logs. More consistent protocol reporting and better use of device logs/sensor data to explain mechanisms and delivered dose would improve comparability and accelerate translation.

8.2 Personal mobility exoskeletons

8.2.1 Mechanical design and ergonomics

Gap: many lightweight devices show reduced metabolic cost in controlled walking or running, but barrier tasks (stairs, inclines, loaded stepping) require higher joint moments, which pushes designs toward higher torque capacity and often higher limb mass. A review of (quasi-)passive lower-limb devices reports masses from 0.3–13.87 kg, with most systems below 3 kg, showing the pressure to stay lightweight for wearable use.[9] In contrast, a stair-focused powered knee exoskeleton reports driving torques up to 180 Nm with a 2.9 kg leg segment (knee + thigh), illustrating why barrier-capable designs face a severe torque–mass trade-off.[25]
Opportunity: treat stairs and inclines as core design targets (not add-ons) and use compact torque-capable architectures while limiting distal mass so the device remains wearable in daily transitions.

Gap: current work emphasises that mass located away from the body's centre of gravity increases metabolic cost and reduces comfort, which can reduce or cancel the net benefit of assistance during long-wear or higher-speed locomotion.[17]
Opportunity: keep distal segments light by architecture. Place heavier components near the waist/trunk and use mechanical layouts or transmissions that minimise added mass at the shank and foot when possible.

8.2.2 Actuation and power supply

Gap: portable powered systems can support structured use but often remain limited for continuous all-day wear. For example, one hip system reports about 2 hours of continuous walking at 3 km/h and maximum noise below 60 dB at 1 m, which is compatible with planned sessions but still constraints long-duration, day-long use.[18]
Opportunity: design and report autonomy around real routines. Define whether the intended use is short daily sessions, longer community outings, or extended wear, and design charging, battery swapping, and performance expectations around that use model.

Gap: in some high-assistance portable designs, the main limitation is not torque output but how quickly parts wear. For example, a twisted-string ankle running exoskeleton reported a minimum string lifespan of 3 min 22 s when providing 43 Nm peak torque, requiring string replacement between trials. This level of maintenance is not compatible with everyday personal use.[30]
Opportunity: design around service interval and maintainability, not peak torque alone. For personal mobility systems, maintenance frequency must fit daily life. Transmission choices should be evaluated by service interval and ease of replacement (time, tools, and cost) as well as by the torque they can deliver.

8.2.3 Human–device interface and comfort

Gap: long-wear tolerance is under-documented relative to its impact on adoption. Many studies quantify short-term benefit but do not fully characterise comfort over long wear and repeated don/doff cycles, even though these factors often decide whether a device is used consistently outside research protocols.[16]
Opportunity: treat comfort as the ceiling on usable assistance. Design around pressure/friction management and repeatable fit, and report donning/doffing time as a core feasibility metric (for example, the 30 s donning / 5 s doffing benchmark reported for a 2.466 kg concept).[46]

8.2.4 Sensing and perception

Gap: simple sensing can mis-time assistance during real walking. Many devices use basic gait-phase sensing (for example, foot contact) to decide when to assist. This can work during steady, straight walking, but it can be less reliable during turns, speed changes, uneven ground, or task switching. When timing is wrong, assistance can feel unnatural and reduce user confidence.
Opportunity: use a small number of sensors that improve timing and scaling. Instead of adding many sensors, add only sensing that directly helps match assistance to the user's

demand. For example, one ankle exoskeleton uses plantar pressure sensing and a torque sensor to estimate biological ankle moment and scale assistance as a fraction of that estimate; the study cites prior validation reporting >90% accuracy for pressure-based ankle-moment estimation.[31]

8.2.5 Control strategies and AI

Gap: passive clutch designs highlight failure modes in non-steady gait (for example, undesirable locking during rapid deceleration), which motivates explicit safe disengagement modes.[32] Stair-ascent control also depends on stable phase switching and smooth transitions, reinforcing that good steady assistance is not sufficient for real community mobility.[50]
Opportunity: treat transitions as the benchmark, not an edge case. Validate start/stop, speed changes, deceleration, turning, and stairs explicitly, because these conditions often determine perceived safety and usability in daily life.

Gap: user adaptation changes measured benefit and timing. In older adults using ankle assistance, the minimum metabolic power occurred around 6.6 ± 1.6 min, and minimum soleus iEMG occurred around 6.0 min and was 17% lower than no-assistance, showing that short exposures may underestimate stable benefit and that familiarisation is part of real performance.[31]
Opportunity: define the expected familiarisation period and provide feedback or support that helps users reach stable benefit sooner and more safely.

8.2.6 Safety mechanisms

Gap: many studies remain supervised and time-limited, while real personal use requires safe behaviour during unexpected events (snagging, mis-steps, loss of balance).[29]
Opportunity: make safety responses part of the core feature set. Community-focused devices include explicit protective behaviours (for example, torque-off if clothing is caught), and balance recovery research treats instability detection and recovery assistance as a dedicated wearable function rather than a secondary add-on.

8.2.7 Usability and acceptance

Gap: even when users complete protocols safely, they may still request improvements in weight, noise, and design, factors that directly influence whether a device is worn routinely. Qualitative evidence shows that acceptance also depends on comfort, dignity, and a realistic learning pathway aligned with user routines and preferences.[16]
Opportunity: design for “liveability.” Reduce burden (weight/noise/maintenance), support learning, and plan integration with existing mobility aids when needed.

8.3 Industrial exoskeletons

8.3.1 Mechanical design and ergonomics

[50] Zhang et al., 2021. Active knee joint exoskeleton for stair ascent augmentation. Science China Information Sciences, 64(3), 139204.

Gap: industrial devices can show benefits in controlled tasks but become less effective (or create new problems) when they restrict movement in dynamic workflows. This gap between controlled evaluations and real stations is repeatedly described as a lab-to-field challenge.[10]

Opportunity: design and evaluate around workflow variability. Ensure devices preserve workspace and allow the range of motion needed in real work cycles, not only in single-task demonstrations.

Gap: posture supports can shift loads but may also create discomfort and perceived risk. Lower-limb posture support evidence reports large reductions in muscular demand (about 30–90%) and plantar pressure (about 54–80%) in supported postures, but also reports discomfort and “unsafe feeling” as barriers.[34]

Opportunity: design and validate pressure distribution, stability, and transition behaviour (walking-to-support and support-to-walking) as core performance criteria.

8.3.2 Actuation and power supply

Gap: powered adaptability is desirable, but passive simplicity dominates deployment. Passive systems dominate because they avoid charging and maintenance logistics and reduce weight/noise burdens, especially for shoulder supports in production environments.

Opportunity: where adaptability is needed, prioritise low-burden tuning or semi-active assistance that can be adjusted per station without introducing high maintenance overhead.

8.3.3 Human–device interface and comfort

Gap: long-wear comfort and heat build-up can limit real use. Industrial exoskeletons may need to be worn for several hours. If the device causes discomfort, heat build-up, or is difficult to put on and adjust correctly, workers may stop using it even when short studies show reduced muscle activity.

Opportunity: improve the fit and contact interface for shift use. Design the straps and pads so fit is repeatable and does not drift during a shift, which reduces pressure hot spots. Use liners or contact materials that can be cleaned easily or swapped, since devices are often shared between workers.

8.3.4 Sensing and perception

Gap: sensing often supports research measurement rather than operational management. Evidence mapping shows many metrics and tasks, but limited standardisation and limited translation into indicators that organisations can track over time.[36]

Opportunity: use minimal sensing only when it outputs operationally useful indicators. Use durable sensor stacks (e.g., IMUs or load sensing where relevant) when they produce stable, interpretable indicators that can feed into safety and ergonomics processes.

8.3.5 Control strategies and AI

Gap: intent-aware control is promising but not field-proven. Intent prediction for active upper-limb industrial exoskeletons has strict timing constraints: one review includes 29 studies and reports prediction windows from about 450 ms before to 660 ms after motion onset, highlighting the difficulty of delivering timely assistance under real workflow variability.[43]

Opportunity: keep safety-critical control deterministic and use prediction conservatively. Use intent prediction for advisory functions, bounded mode switching, or tuning support rather than relying on it for continuous high-authority torque delivery in uncontrolled workflows.[43]

8.3.6 Safety mechanisms

Gap: safety evaluation is inconsistent, and side effects are under-tracked. Methodology reviews note that safety aspects are not consistently addressed and study designs are heterogeneous, limiting confidence about side effects and long-term risk.[35] Meta-analytic evidence also stresses that assistance can shift load to non-target regions, so evaluation must look beyond the supported joint or muscle group.[3]

Opportunity: standardise side-effect monitoring in validation and procurement. Require monitoring of non-target regions and compensations as part of industrial evaluation, not only changes in the targeted muscle group.

8.3.7 Usability and workflow fit

Gap: devices may help in static tasks but hinder in dynamic cycles, and workers may remove devices during non-target tasks, reducing real exposure benefit over the shift.[10]

Opportunity: pair devices with clear task selection and station presets and validate compatibility with PPE and mixed-task cycles.

8.3.8 Evidence and validation gaps

Gap: the literature is large, but comparability remains limited. Evidence mapping reports 139 eligible studies across 33 back exoskeletons, 25 shoulder exoskeletons, and 18 other unique systems, breadth without consistent benchmarking.[36]

Opportunity: use frameworks that combine metrics, tasks, and postures to compare devices and reduce lab-to-field uncertainty.

8.4 Cross-domain opportunity map (what would move the field fastest)

The opportunities below recur across rehabilitation, personal mobility, and industrial use and repeatedly limit real deployment.

1. **Design for transitions and real-world variability, not only steady tasks.**
   Across domains, failures and user rejection often happen during transitions. Rehabilitation systems must switch modes safely beyond steady treadmill gait, personal mobility must remain stable during turns and speed changes, and industrial systems must function across mixed task cycles rather than a single posture.
2. **Make the human–device interface a core engineering priority.**
   Comfort, pressure distribution, and repeatable fit set the ceiling on wear time and delivered benefit. If the interface creates hot spots or shifts during use, the device will not be worn long enough to matter, regardless of its mechanical capability.
3. **Generate evidence around sustained use, not only short demonstrations.**

The evidence base still under-represents long-term use: follow-up is limited in rehabilitation (e.g., 12.58% of studies included follow-up in one review), long-duration field studies are uncommon in industry, and personal mobility studies are largely supervised and time-limited.[7]

4. **Use sensing and control that improve performance without increasing operational burden.**
   The most deployable pattern is a clear, deterministic safety core, with additional intelligence used for tuning, monitoring, and decision support. Complex sensing and control that increases setup time, calibration demands, or failure modes is a barrier to adoption in clinics, homes, and workplaces.
5. **Treat durability and serviceability as explicit requirements for daily contexts.**
   A device that needs frequent maintenance will not be used routinely. This is especially visible in personal mobility prototypes where component life can be minutes under load, and it also applies in industrial deployments where predictable maintenance and hygiene processes are essential.
6. **Standardise reporting so results can be compared and improved.**
   Progress is slowed when basic feasibility parameters are missing or inconsistent. For example, one rehabilitation mechanical review reported that 63.46% of designs did not report device weight, and industrial studies use heterogeneous tasks and methods, which makes comparisons and procurement decisions difficult

Table 4 summarises cross-domain opportunities and pairs each one with a practical next-step target.

Table 4. Cross-domain Opportunity Matrix

Opportunity area	User/setting requirement	Design levers	Evidence basis (from literature)	Next-step target
1) Transitions and non-steady conditions (start/stop, speed changes, turns, stairs, perturbations, task switching)	Rehab: safe progression beyond steady treadmill cycles. Mobility: safe community walking with barriers. Industry: mixed-task workflows without interference.	Control architecture + sensing + mechanical allowances at key joints	Transition instability and mode switching are recurring limitations in control pipelines.[24] Non-steady failure modes such as undesirable locking during rapid deceleration are reported in clutch-based designs.[32] Workplace benefits vary in dynamic workflows.[10]	Define a transition test battery and pass it before claiming "real-world ready": (i) start/stop, (ii) speed change, (iii) turn, (iv) step-up/step-down or stair segment (mobility), (v) deceleration event (mobility), (vi) task switch / cross-body reach / walking-between-stations segment (industry). Publish stability and failure-response behaviour per test.
2) Interface comfort as a primary design spec (pressure, hot spots, repeatability)	All domains: tolerance, adherence, and willingness to wear the device long enough to matter.	Human–device interface engineering (pads, cuffs, strap paths, compliance, sizing, quick-adjust)	Interface issues and fit strongly influence tolerance; many designs do not report pressure distribution.[44] Users/caregivers emphasise acceptance and burden in daily life.[16] Worker acceptance is shaped by discomfort and ease of use.[19]	Add measurable interface criteria: (i) pressure mapping or equivalent proxy during key tasks, (ii) repeatability of fit across sessions/shifts, (iii) discomfort map logging, (iv) time-to-fit. Report these alongside performance outcomes (rehab tests; mobility economy/barriers; industrial EMG/task metrics).
3) "Used in practice" validation, not just "works in a trial" (longer exposure,	Rehab: durable functional gains and service feasibility. Mobility: daily adherence and	Study design + operational instrumentation (logs,	Rehab evidence includes limited follow-up (12.58% in one large review) and high	Add a realistic-duration layer to every study. Rehab: include follow-up and report session adherence + setup time. Mobility: include

Opportunity area	User/setting requirement	Design levers	Evidence basis (from literature)	Next-step target
follow-up, real settings)	independence. Industry: shift-scale use and side effects.	adherence, incidents)	heterogeneity.[8] Personal mobility has strong supervised evidence but limited unsupervised daily-use data.[29] Industrial evidence is broad (139 studies across many device types) but field standardisation and long-duration outcomes remain limited.[36]	home/community "carry" periods or repeated real-environment sessions with adherence logs.[2] Industry: run multi-shift pilots with exposure logs, discomfort maps, and task-cycle compatibility checks.[6]
4) Minimal-but-informative sensing that reduces burden	Rehab: reduce setup time while enabling personalisation/safety monitoring. Mobility: robustness under variability without heavy calibration. Industry: operational KPIs that are trackable.	Sensor set selection + signal processing pipeline + logging	Rehab devices often rely on encoders/IMUs/foot contact; richer sensing is valuable but increases burden.[7] Biomechanics-linked sensing can be practical when purposeful.[31] Industrial literature shows heterogeneity and need for standardised, operationally useful measures.[35]	Define a baseline sensor stack per domain: Rehab: encoders + limited IMUs + simple contact/pressure; Mobility: IMU + contact plus optional pressure-linked moment estimation where it improves assistance matching;[31] Industry: minimal IMUs/load proxies only if they feed stable KPIs. Require that every added sensor has a stated operational purpose and does not add unacceptable setup time.
5) Interpretable control with bounded adaptation (certifiable, transparent, still user-specific)	Rehab: safe assist-as-needed without black-box behaviour. Mobility: stable switching and predictable behaviour. Industry: reliability over shifts and varied tasks.	Control structure (state machine + bounded parameters) + supervision layer	Adaptive strategies are discussed widely but appear in a minority of clinically reported systems.[8] Learning-based methods face translation constraints.[45] Industrial intent prediction has strict timing windows and limited field proof.[43]	Keep the safety loop deterministic and expose adjustable parameters. Implement adaptation as bounded tuning (e.g., state-dependent impedance/assistance scaling) with clear limits and logs. If learning is used, keep it in supervisory roles (drift detection, parameter suggestions, anomaly alerts) rather than direct torque injection.[51]
6) Durability/ serviceability as a top-tier requirement (especially mobility + industry)	Mobility: daily use without frequent failure or maintenance. Industry: predictable upkeep and hygiene in shared fleets.	Transmission design, wear parts, modular replacement, maintenance workflow	Durability bottlenecks can be extreme: twisted-string running assistance reported ~3 min 22 s minimum lifespan under high torque.[30] Industrial adoption depends on maintenance planning and practical deployment processes.[19]	Set a service-interval requirement (hours/weeks, not minutes). Use modular wear parts and define replacement time and tools needed. For industry, include cleaning/liner swap workflows and "fit drift" checks across a shift.[19]
7) Standardised reporting to enable comparison	All domains: faster iteration, clearer procurement decisions, more transferable findings.	Reporting template + shared metrics	Rehab mechanical reporting gaps are large (e.g., weight missing in 63.46% of surveyed designs in one review).[44] Industrial evidence is large but hard to	Add a one-page "device spec + use protocol" sheet for every system: mass + mass distribution, size range, don/doff time, sensor set, control modes, safety limits, and the exact task battery used. Require consistent outcome reporting per domain (rehab functional scales; mobility

[51] Mashud et al., 2025. Advances in Control Techniques for Rehabilitation Exoskeleton Robots: A Systematic Review. Actuators, 14(3), 108. doi: 10.3390/act14030108.

Opportunity area	User/setting requirement	Design levers	Evidence basis (from literature)	Next-step target
			compare across devices/tasks.[36]	functional + economy + barriers; industry EMG/posture + task time + discomfort).