Comprehensive Information and Recommendations on

THE UTILISATION OF EXOSKELETON SOLUTIONS

and the Latest Innovative Technologies

Organiser:

hkpc 生產力局

Funding Organisation:

創新科技署 Innovation and Technology Commission

政府資助計劃

Sponsor:

ROHDE&SCHWARZ Make ideas real

Supporting Organisations:

職業安全健康局 Occupational Safety & Health Council

香港建造商會 Hong Kong Construction Association

Disclaimer

Any opinions, findings, conclusions or recommendations expressed in this material/event (or by members of the project team) do not reflect the views of the Government of the Hong Kong Special Administrative Region, the Innovation and Technology Commission or the General Support Programme Vetting Committee of the Innovation and Technology Fund.

This e-booklet is for information purposes only. Whilst every effort has been made to ensure information accuracy, the publisher and associated organisations of the project cannot be held responsible for any damage resulting from the use and application of information herein contained.

Enquiry:
For enquiries regarding wearable robotics and exoskeleton solutions, please contact the Smart City Division of the Hong Kong Productivity Council at 2788 5098 or wtlam@hkpc.org.

Hong Kong Productivity Council
HKPC Building, 78 Tat Chee Avenue, Kowloon, Hong Kong
Tel: (852) 2788 5678
Fax: (852) 2788 5900
Website: https://www.hkpc.org
E-mail: hkpcenq@hkpc.org

Published: April 2026

Innovation and Technology Fund
General Support Programme
"Promoting Exoskeleton Applications and Technologies in Hong Kong Industries to Enhance Occupational Safety"

About this E-booklet

"Promoting Exoskeleton Applications and Technologies in Hong Kong Industries to Enhance Occupational Safety" is a project supported by the Innovation and Technology Fund - General Support Programme (GSP) and organised by the Hong Kong Productivity Council (HKPC).

The project aims to improve occupational safety in logistics, health care and construction industries as well as the public sector by introducing wearable robotics solutions and cutting-edge technologies, such as the Internet of Things (IoT), robotics and automation, virtual and augmented reality (VR & AR). A symposium, four technical workshops and an e-booklet have been delivered to provide comprehensive information and recommendations to the industries and the public.

This e-booklet could help participants and the public understand how to implement these technologies and visualise their benefits in various contexts. Additionally, this e-booklet is instrumental to enhancing occupational safety and health, promoting productivity and reducing physical strain and injuries.

Acknowledgements

We would like to thank the following organisations and parties for their support for this project (Names in alphabetical order).
Hong Kong Construction Association
Hong Kong Productivity Council
Occupational Safety & Health Council
Rohde & Schwarz Hong Kong Limited

TABLE OF CONTENTS

INTRODUCTION AND OVERVIEW OF THE LATEST INNOVATIVE TECHNOLOGIES AND APPLICATIONS THAT ADDRESS OCCUPATIONAL SAFETY AND HEALTH CHALLENGES

Chapter 1 – Introduction and Overview of the Latest Innovative Technologies and Applications that Address Occupational Safety and Health Challenges

1.1 Occupational Safety and Health Challenges in Modern Workplaces

Occupational Safety and Health (OSH) remains a critical concern for both industries and the public worldwide. Despite continuous improvements in regulations, training and the safety culture, there are still substantial human, societal and financial consequences associated with workplace accidents, injuries and occupational diseases. According to international estimates, thousands of workers lose their lives each day due to unsafe working environments, while many more suffer from long-term disabilities caused by physical strain, fatigue and musculoskeletal disorders.

High-risk industries, such as construction, manufacturing, logistics, maintenance and utilities, are particularly vulnerable. In construction environments, for example, workers have to deal with constantly changing job sites, heavy machinery, working at heights, confined spaces and dynamic interactions between people and equipment. These conditions create a complex risk landscape where traditional safety measures—such as signage, manual supervision and periodic inspections—are often insufficient to prevent accidents in real time.

In Hong Kong, the construction sector has consistently recorded fatality rates way above the overall industrial average. Recognising these challenges, regulatory bodies have strengthened occupational safety legislation, increased penalties for non-compliance and promoted proactive safety management approaches. However, compliance alone does not eliminate all risks. There is an increasing recognition that **innovation technology** must play a critical role in enhancing workplace safety, reducing physical workload and supporting a more resilient and sustainable workforce.

1.2 From Reactive Safety to Proactive and Intelligent Prevention

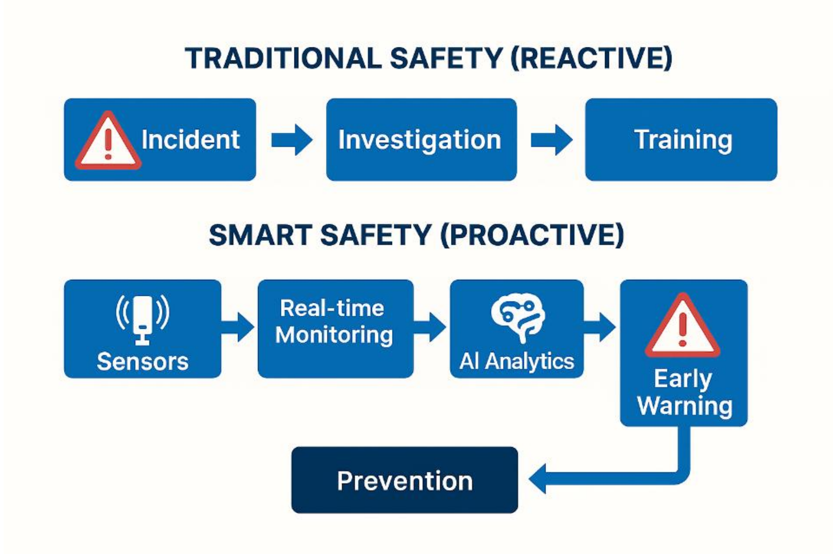
Traditional OSH practices are largely reactive. Incidents are investigated after they occur, corrective actions are introduced and lessons learned are incorporated into future training. While this approach is essential, it often fails to protect workers from immediate and rapidly evolving hazards.

The emergence of advanced digital and robotic technologies enables a fundamental shift—from reactive safety management to **proactive, predictive and preventive safety systems**. Organisations can now continually monitor hazards, prevent accidents caused by unsafe conditions and intervene automatically or through timely alerts by integrating sensing, data analytics, artificial intelligence (AI) and human-centred robotics.

This transformation is driven by several converging innovation technology trends:

- The rapid development of the **Internet of Things (IoT)** and **Artificial Intelligence of Things (AIoT)**
- Advances in **robotics and wearable exoskeleton technologies**
- Increased adoption of **automation and smart machinery**
- Immersive **Virtual Reality (VR) and Augmented Reality (AR)** technologies for training and operational support

These technologies do not replace traditional safety measures; instead, they enhance them by providing real-time awareness, data-driven insights and physical assistance to workers.



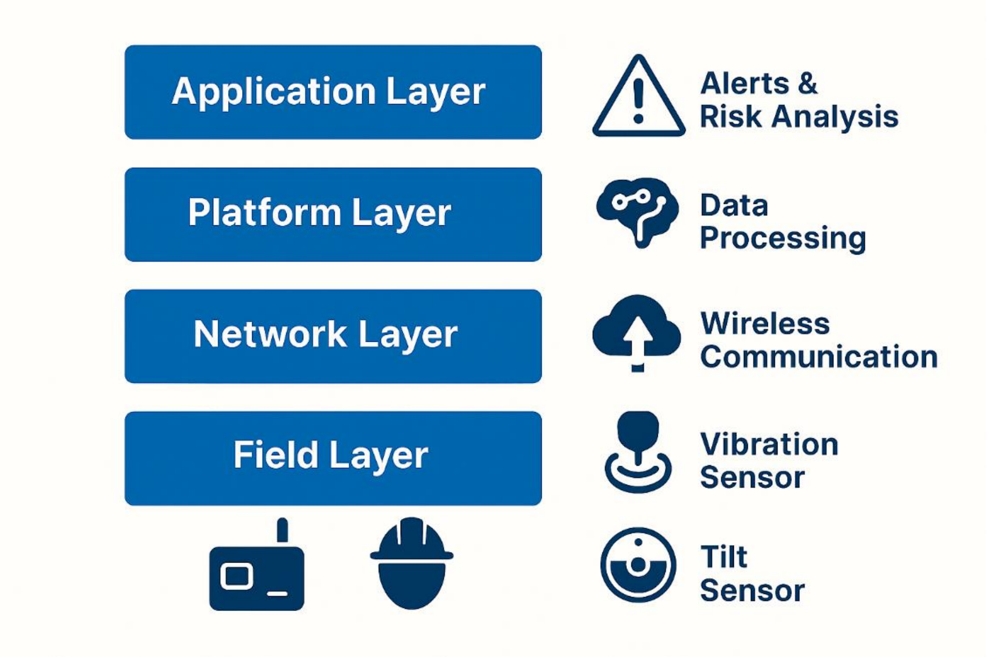
Sections 1.3 to 1.7 below provide an overview of the latest innovative technologies that are the bedrock of smart occupational safety systems. They include Internet of Things (IoT) solutions, robotics and automation, virtual reality (VR), augmented reality (AR), wearable robotics and exoskeletons and integrated smart safety ecosystems. When deployed individually, each technology contributes to improving safety awareness, reducing physical and cognitive workload and minimising exposure to workplace hazards. When integrated, they enable comprehensive safety intelligence—connecting people, equipment, environments and management systems in real time.

1.3 Internet of Things (IoT) and AIoT for Occupational Safety

1.3.1 Concept of IoT-Enabled Safety Systems

IoT refers to interconnected networks of sensors, devices and equipment that collect, transmit and analyse data in real time. When applied to OSH, IoT systems enable continuous monitoring of workers, equipment and environmental conditions.

It is increasingly common for modern safety solutions to adopt **AIoT** which combines IoT data with artificial intelligence. AI algorithms analyse large volumes of sensor data to detect patterns, anomalies and early warning signals that may not be apparent from human observation alone.



1.3.2 Real-Time Location and Danger Zone Monitoring

Real-time location systems are among the most impactful IoT applications in safety-critical environments. Using advanced positioning technologies, such as Ultra-Wideband (UWB), workers and assets can be tracked with centimetre-level accuracy in both indoor and outdoor environments.

UWB-based danger zone alert systems can define virtual safety boundaries around hazardous areas, mobile plants or tower cranes. When a worker wearing a smart tag approaches a restricted zone, the system triggers immediate visual, audio or vibration alerts. Simultaneously, site managers receive real-time notifications through a centralised platform to enable rapid intervention.

Such systems significantly reduce:

- Collisions between workers and heavy machinery
- Unauthorised entry into hazardous zones
- Accidents involving blind spots and poor visibility

Unlike traditional warning signs or barriers, IoT-based systems are **dynamic, adaptive and data-driven**, adjusting automatically as site conditions change.

1.3.3 Structural, Vibration and Environmental Monitoring

IoT sensors also play a critical role in monitoring structural integrity and environmental safety. High-precision tilt and vibration sensors can continuously assess buildings, scaffolding, temporary structures and machinery. Even minor deviations or abnormal vibration patterns can be detected early and analysed through cloud-based platforms.

By combining real-time sensing with data analytics, organisations can:

- Detect early signs of structural instability
- Monitor machinery health and prevent mechanical failures
- Reduce risks associated with sudden collapses or equipment malfunction

In addition to enhancing worker safety, these preventive capabilities also improve productivity and asset lifespan.

1.4 Robotics and Automation in Occupational Safety

1.4.1 The Role of Robotics in Hazard Reduction

Robotics and automation have long been used to improve productivity and quality. They are increasingly recognised as powerful tools for **risk reduction**. Robots can be deployed to perform repetitive, physically demanding or hazardous tasks that expose workers to injuries.

In industrial and construction settings, automation can reduce human exposure to:

- Heavy lifting and repetitive motions
- Toxic substances or extreme temperature environments
- Confined spaces or unstable environments

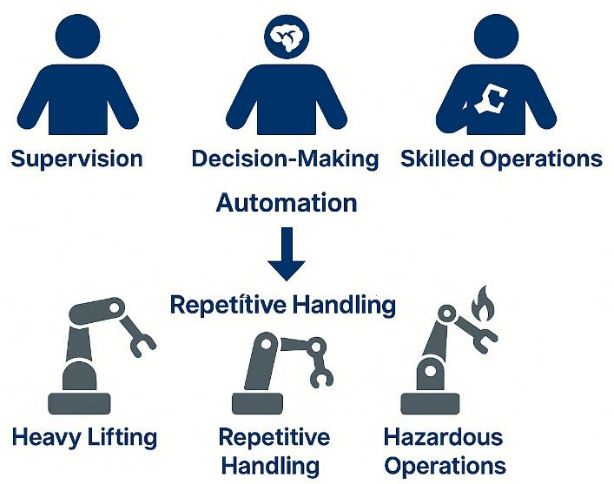
By reallocating such tasks to machines, organisations can significantly lower injury rates and reduce long-term health impacts.

1.4.2 Human–Robot Collaboration

Modern robotics is evolving beyond traditional rigid automation to **collaborative and assistive technologies** built to work safely with people. These systems emphasise adaptability, compliance and human-centred control.

Assistive robots and wearable robotics, such as exoskeletons, do not replace workers. Instead, they **augment human capabilities**, enabling workers to perform tasks more safely and efficiently while reducing physical strain.

This shift toward human–robot collaboration is particularly important in aging societies and labour-intensive industries where maintaining a safety, healthy and productive workforce is a growing challenge.



1.5 Wearable Robotics and Exoskeleton Solutions

1.5.1 Rationale for Wearable Robotics in OSH

Musculoskeletal disorders are among the most common occupational health issues, often resulting from repetitive tasks, awkward postures and manual handling of loads. Wearable robotic systems—commonly referred to as exoskeletons or exosuits—are designed to address these challenges directly.

Wearable robotics provide mechanical support to specific body parts, such as the back, shoulders, knees, hips or ankles. By assisting movement and sharing load forces, these systems reduce muscle fatigue, joint stress and risk of injury.

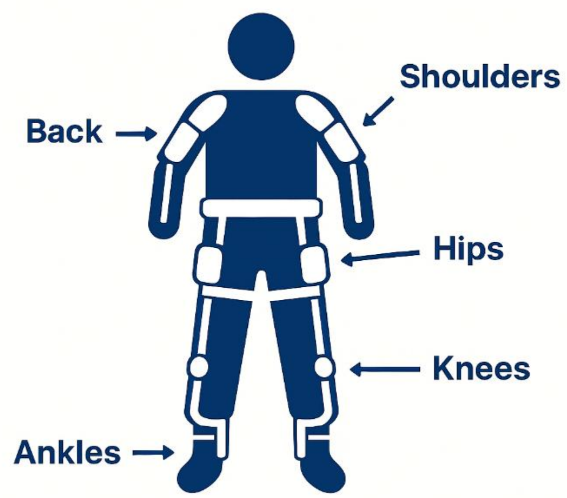
1.5.2 From Rigid Exoskeletons to Soft Assistive Robots

Early exoskeleton designs were often large, rigid and heavy, limiting their practicality for everyday use in the workplace. Recent advances have shifted toward **lightweight, soft and compliant wearable robots** that align more naturally with human biomechanics.

Key design principles include:

- Personalised and user-centric design
- Lightweight and compact structures
- Compliance and comfort for extended wear
- Adaptive and real-time assistance based on user intention

These innovations make wearable robots increasingly viable for long-duration tasks in real workplace environments.



1.5.3 Safety and Productivity Benefits

When properly implemented, wearable exoskeleton solutions can:

- Reduce physical strain and muscle fatigue
- Prevent acute injuries and long-term musculoskeletal disorders
- Extend the working capacity of aging workers
- Improve endurance and task consistency
- Enhance overall productivity without compromising safety

By supporting the body rather than replacing it, wearable robotics align well with modern OSH principles that emphasise prevention, well-being and sustainability.

1.6 Virtual Reality (VR) and Augmented Reality (AR) for Safety Enhancement

1.6.1 Immersive Safety Training with VR

Virtual Reality (VR) provides immersive, simulated environments where workers can experience hazardous scenarios in complete safety. Unlike traditional classroom training, VR allows participants to interact with realistic situations, make decisions and experience the consequences without real-world risks.

VR-based safety training is particularly effective for:

- High-risk scenarios that are difficult or dangerous to reproduce
- Emergency response drills
- Equipment operation and hazard recognition

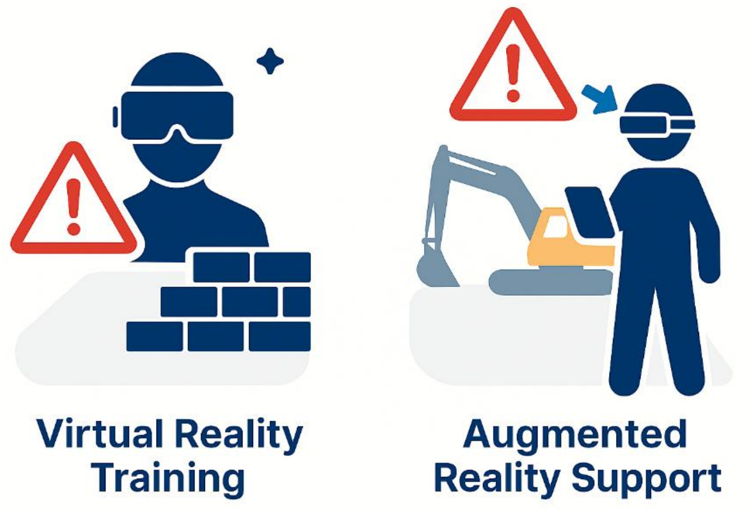
This type of immersive training improves retention, situational awareness and confidence, leading to safer behaviour on site.

1.6.2 Real-Time Operational Support with AR

Augmented Reality overlays digital information onto the real world, typically through smart glasses or mobile devices. In operational settings, AR can provide workers with:

- Step-by-step procedural guidance
- Real-time hazard alerts
- Visualisation of hidden utilities or structural elements
- Remote expert assistance

By delivering relevant information at the point of work, AR reduces human errors, improves task accuracy and enhances safety outcomes.

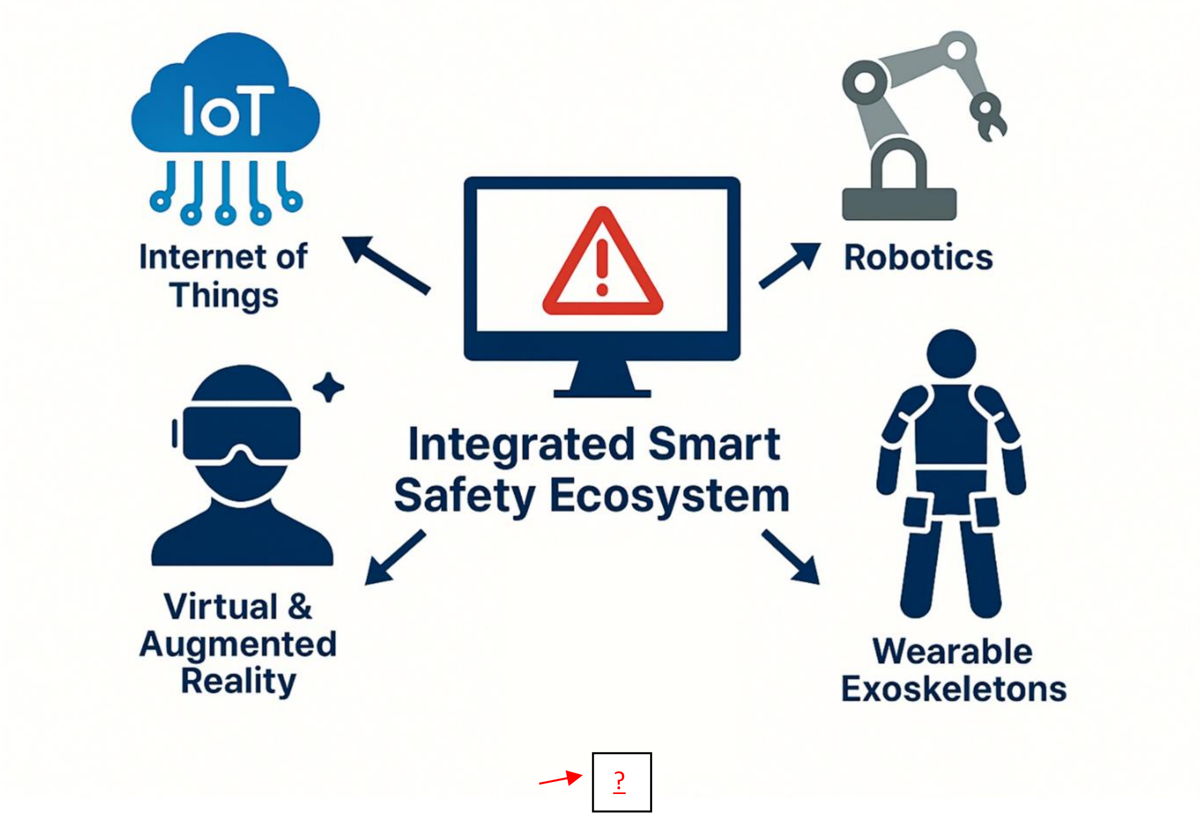


1.7 Integrated Smart Safety Ecosystems

The true power of modern safety innovation lies in **integration**. IoT sensors, wearable robots, robotic systems and immersive technologies are most effective when deployed as part of a unified safety ecosystem. Such a centralised platform enables:

- Data fusion from multiple sources
- Real-time visualisation and analytics
- Predictive risk assessment
- Continuous improvement through data-driven insights

These integrated systems elevate OSH management beyond regulatory compliance and incident response toward **intelligent, adaptive and resilient safety operations**.



1.8 Looking Forward: Safer and Smarter Workplaces

As workplace environments become more complex and labour demands increase, the adoption of advanced technologies is essential. IoT, robotics, wearable exoskeletons and VR/AR provide practical and proven pathways to enhance occupational safety, protect workers' health and improve productivity simultaneously.

This e-booklet aims to help participants and the public understand not only what these technologies are, but **how they can be implemented**, **why they matter** and **what benefits they deliver**. By embracing innovation and fostering collaboration between technology developers, employers, workers, the public and regulators, we can build safer, more efficient and more sustainable workplaces for the future.

TYPES OF WEARABLE ROBOTICS AND EXOSKELETON SOLUTIONS

Chapter 2 – Types of Wearable Robotics and Exoskeleton Solutions

2.1 Introduction: From Ergonomic Aids to Human-Centric Robotics

Wearable robotics and exoskeleton solutions represent a significant evolution in occupational safety and assistive technology. Unlike conventional ergonomic tools or mechanised equipment that operate externally to the human body, wearable robotic systems are designed to work **in direct synergy with the user's musculoskeletal system**. By providing mechanical assistance, redistributing loads or supporting posture and movement, these systems aim to reduce physical strain, prevent work-related musculoskeletal disorders (WMSDs) and sustain productivity in physically demanding environments.

The global prevalence of WMSDs—particularly those affecting the lower back, shoulders, neck and knees—has been identified as a leading cause of long-term disability and productivity loss across industries. Research evidence from healthcare, emergency services, construction, logistics and manufacturing consistently shows that tasks like manual lifting, bending, twisting, prolonged standing and overhead work are primary contributors to musculoskeletal injury. In response, wearable robotics have emerged as **preventive, assistive and productivity-enhancing solutions**, extending well beyond their original rehabilitative applications.

This chapter provides a comprehensive overview of the **main types of wearable robotics, assistive technologies and exoskeleton solutions**, with emphasis on their operating principles, design classifications, targeted body regions and real-world applications. Drawing on academic research, clinical evaluations and industrial implementation experience, the discussion illustrates how these technologies contribute to safer, healthier and more sustainable work environments.

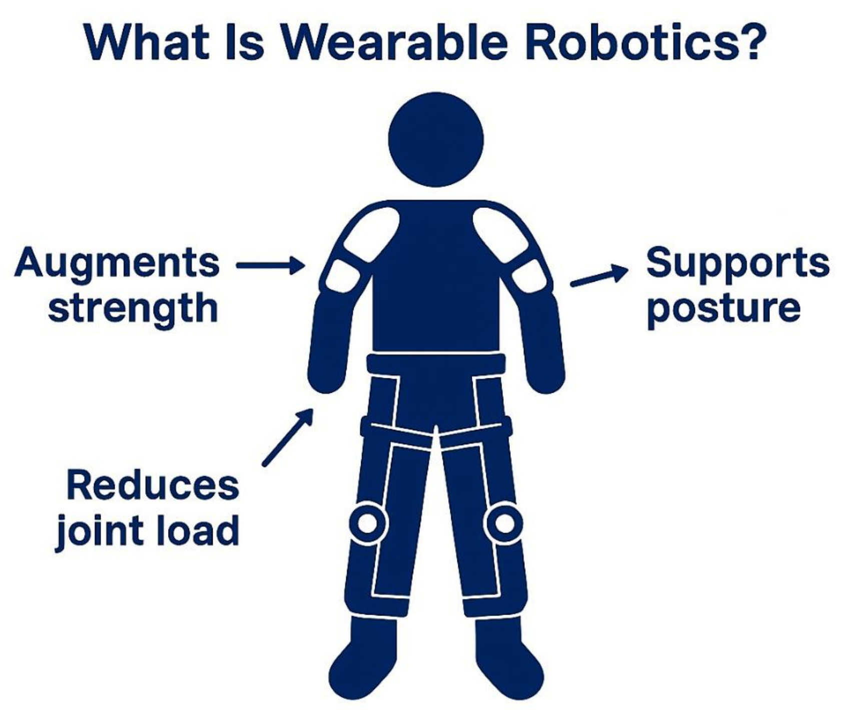
2.2 Defining Wearable Robotics and Exoskeleton Solutions

Wearable robotics can be broadly defined as **mechanical systems worn on the body that augment, assist or support human movement**. Exoskeletons represent a key subset of wearable robotics, and are characterised by an external framework that interfaces with the user's limbs or torso. These systems may assist movement actively through powered actuators or passively through mechanical energy storage and redistribution mechanisms.

In addition to classical exoskeletons, the broader category of wearable assistive technologies includes:

- Soft exosuits
- Hand and grasp assist devices
- Postural support systems
- Hybrid wearable robotic aids

Despite differences in design and complexity, all wearable robotics share a common goal: **to reduce biomechanical load on the human body while preserving natural motion and user autonomy**.



2.3 Classification by Actuation: Active and Passive Wearable Robotics

2.3.1 Active (Powered) Wearable Robotics

Active wearable robotic systems use **external power sources**—such as electric motors, pneumatic actuators or hydraulic systems — to generate assistive forces at joints or body segments. These systems typically incorporate sensors, control algorithms and actuators that respond dynamically to user movement.

Active exoskeletons are capable of delivering **high levels of assistance** and are commonly used in:

- Rehabilitation and physical therapy
- Mobility assistance for individuals with impaired function
- Specialised industrial or military applications

By actively supplying mechanical energy, these systems can significantly enhance strength, endurance and movement capacity. However, their increased system weight, battery limitations, cost and maintenance requirements often restrict their suitability for continuous daily occupational use. As a result, active wearable robotics are most often deployed in **clinical, research or specialised operational contexts** rather than routine industrial tasks.

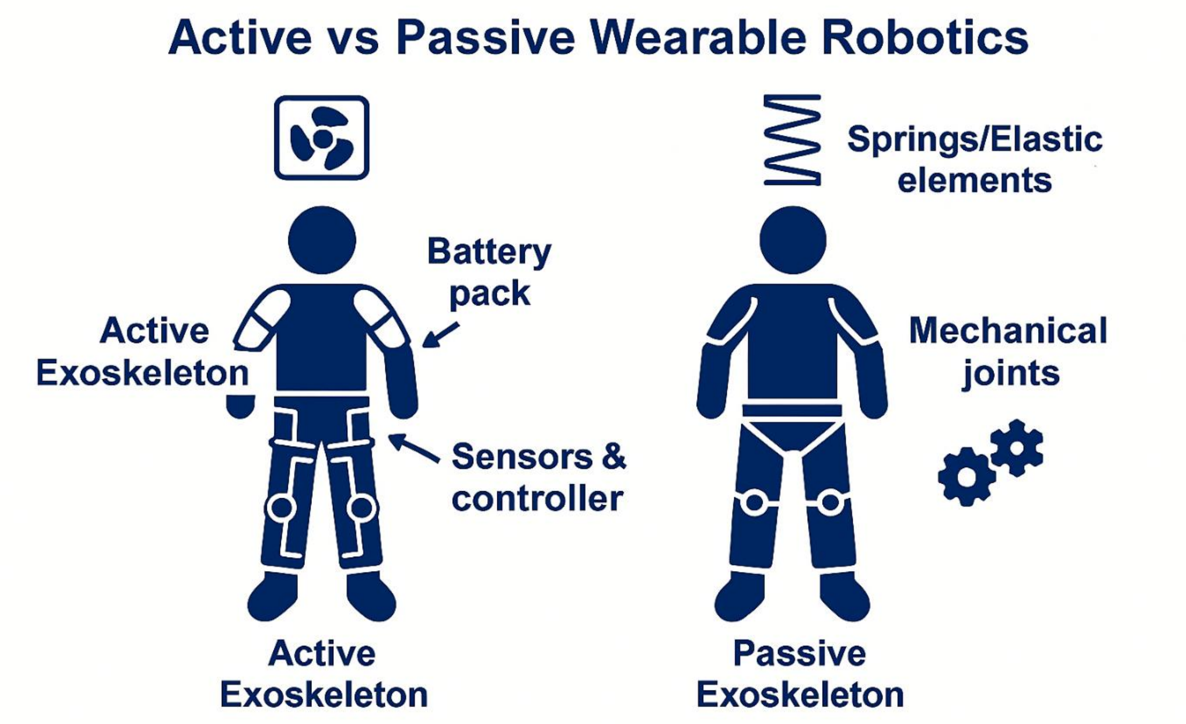
2.3.2 Passive Wearable Robotics and Exoskeletons

Passive wearable robotics represent the **most widely adopted form of exoskeleton technology in real workplaces today**. These systems do not rely on motors or batteries; instead, they use **mechanical elements such as springs, elastic bands or cable-based mechanisms** to generate assistive torque and redistribute forces.

Key characteristics of passive exoskeletons include:

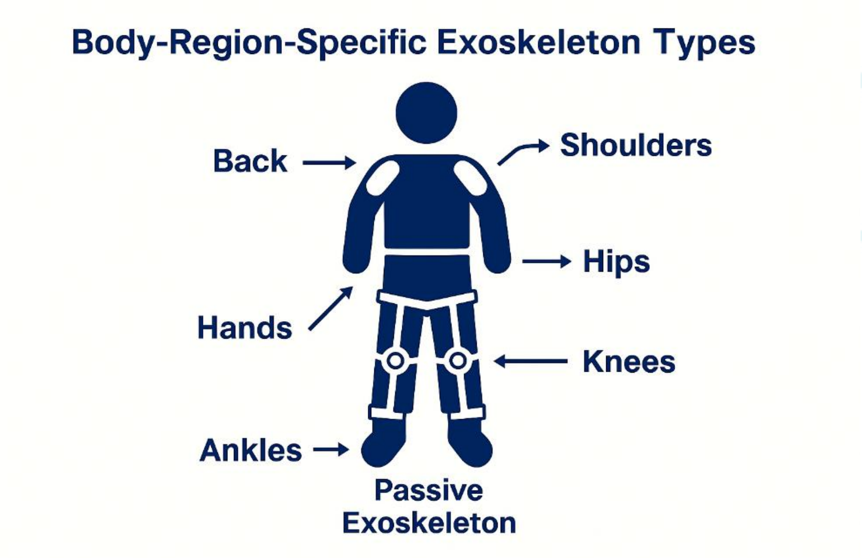
- Lightweight construction
- Intrinsic safety without powered actuation
- Low maintenance requirements
- Ease of use and fast donning/doffing
- Applicability to long working shifts

Passive exoskeletons work by harvesting energy from the user's own movements — such as bending or arm lowering — and returning it to assist subsequent movements. Numerous studies demonstrate that such systems can **significantly reduce muscle activity and perceived exertion** during physically demanding tasks, even without active power input. Because of these advantages, passive exoskeletons are particularly well suited to sectors such as construction, logistics, manufacturing, facility maintenance and healthcare.



2.4 Classification by Targeted Body Region

Wearable robotics and exoskeleton solutions are commonly designed around the **specific anatomical regions** most exposed to occupational strain. This task-oriented design approach enables precise matching of solutions to workplace risk profiles.



2.4.1 Back and Trunk Exoskeleton Solutions

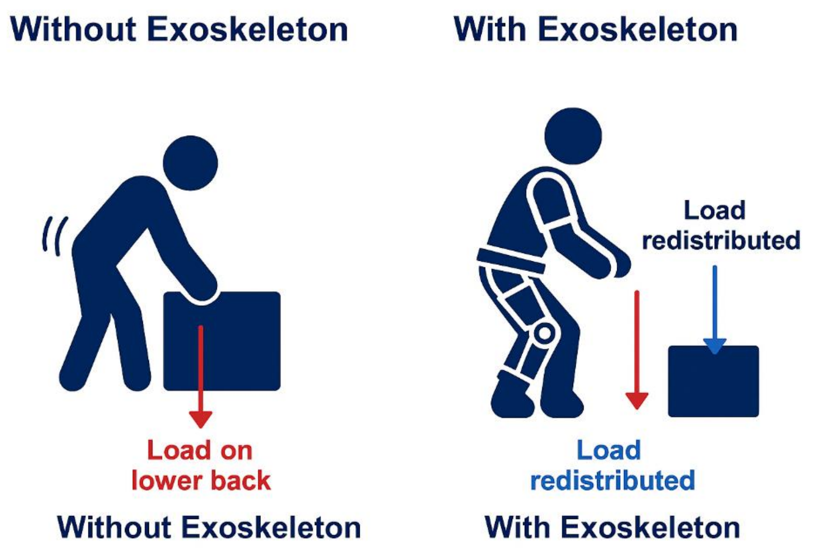
Back and trunk exoskeletons focus on reducing load on the **lumbar spine and surrounding musculature**, which are among the most injury-prone regions in occupational settings. Epidemiological data consistently identify lower back pain as a leading cause of work-related disability.

These systems typically:

- Support trunk extension during lifting
- Transfer load from the spine to the hips or thighs
- Encourage neutral posture during bending and carrying tasks

Industrial versions of passive back exoskeletons have been shown to reduce effective spinal loading by **up to tens of kilograms**, depending on the task and design. Ultralight designs (often below 5 kg) provide meaningful support while preserving freedom of movement.

Research demonstrates that in healthcare and emergency services, passive back exoskeletons can significantly reduce trunk muscle activity during patient transfer, stretcher lifting and cardiopulmonary resuscitation. These reductions are accompanied by lower perceived exertion, suggesting a strong preventive effect against cumulative injury.



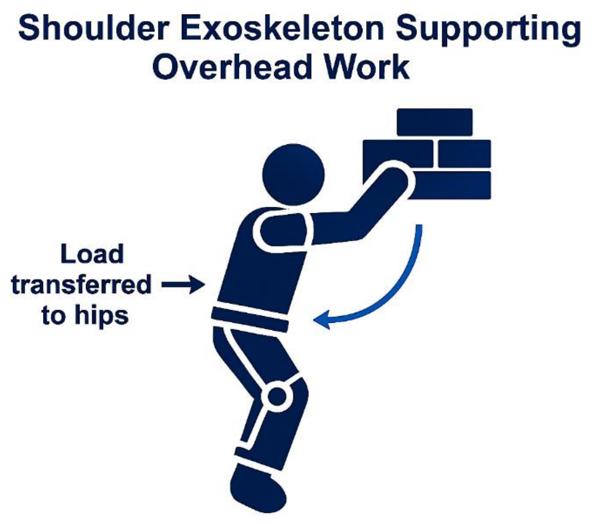
2.4.2 Shoulder and Upper-Limb Exoskeleton Solutions

Shoulder exoskeletons are specifically designed for work involving **prolonged or repetitive arm elevation**, such as overhead installation, maintenance, assembly, and caregiving tasks. These activities impose high continuous loads on the shoulder complex, increasing the risk of fatigue, inflammation and chronic disorders.

Passive shoulder exoskeletons typically:

- Support arm elevation through elastic or cable-based mechanisms
- Transfer arm weight to the torso or hips
- Reduce load on shoulder and neck muscles

Field studies and laboratory measurements indicate **fatigue reductions of approximately 30–40% in shoulder muscles**, along with measurable productivity improvements during overhead work. Importantly, these systems preserve range of motion and do not restrict fine motor control, making them practical for daily use.



2.4.3 Hip, Knee and Lower-Limb Exoskeleton Solutions

Lower-limb exoskeletons assist movements involving:

- Walking and standing
- Squatting and kneeling
- Sit-to-stand transitions
- Load carrying

While initially developed for rehabilitation and mobility assistance, lower-limb wearable robotics are increasingly applied in occupational settings, such as logistics, warehousing and healthcare. These systems can reduce fatigue during prolonged standing and walking and provide joint support during repetitive lifting tasks.

Research involving lower-limb assistance shows reductions in muscle activity and metabolic cost, translating into improved endurance and decreased risk of overuse injuries. Passive configurations emphasising simplicity and comfort are particularly promising for workplace deployment.

2.4.4 Hand, Wrist and Grasp Assist Technologies

Beyond full- body or limb exoskeletons, **hand and finger assistive devices** represent an important category of wearable robotics. These devices focus on:

- Grip assistance
- Load sharing during tool operation
- Reduction of repetitive strain on fingers and wrists

Such technologies are relevant in assembly work, manufacturing, healthcare and laboratory environments. By assisting finger flexion and grip force, hand exoskeletons help reduce tendon strain and hand fatigue during repetitive or force- intensive tasks.

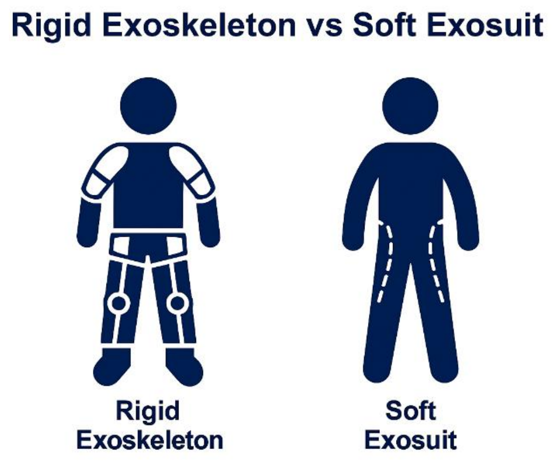
2.5 Soft Wearable Robotics and Exosuits

Traditional exoskeletons often rely on rigid frames and articulated joints. In contrast, **soft wearable robotics (exosuits)** use textiles, flexible cables and compliant materials to deliver assistance while closely conforming to the body.

Soft exosuits offer:

- High comfort and wearability
- Reduced bulk and weight
- Improved user acceptance
- Minimal restriction of natural movement

Although soft systems generally provide lower peak assistance than rigid exoskeletons, their comfort and adaptability make them highly suitable for prolonged use. They are particularly attractive for environments where aesthetic discretion, comfort and freedom of movement are important considerations.



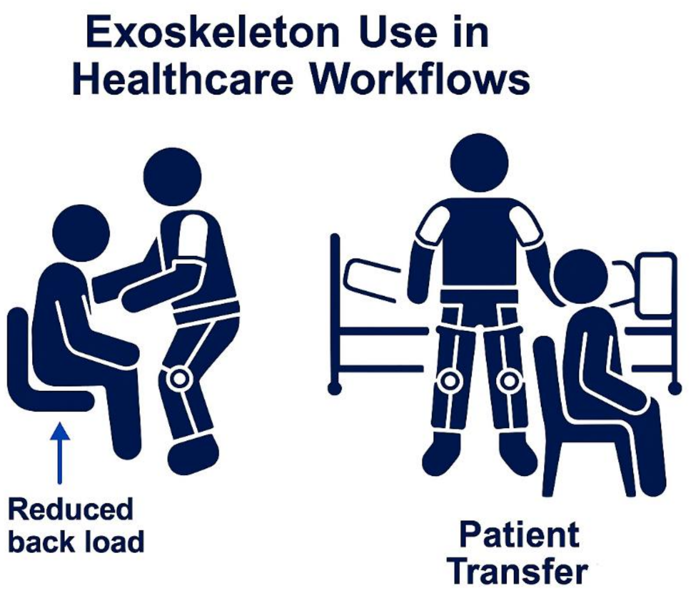
2.6 Wearable Robotics in Healthcare and Care-Related Occupations

Healthcare professionals experience some of the **highest rates of work-related musculoskeletal disorders** among all occupational groups. Tasks like patient transfer, repositioning, prolonged standing and manual handling put substantial strain on the back, shoulders and lower limbs.

Research evidence drawn from clinical studies shows that:

- High prevalence of lower back, shoulder, knee and ankle symptoms
- Significant trunk muscle activation during patient handling
- Measurable reductions in muscle activity when passive exoskeletons are used

Studies evaluating passive back exoskeletons among physiotherapists and ambulance workers report **statistically significant reductions in trunk muscle activity and perceived exertion**, without impairing task performance or safety. User acceptance studies further highlight the importance of comfort, ease of use and non-interference with clinical judgment.



2.7 Productivity, Safety and Organisational Benefits

Beyond individual health protection, wearable robotics deliver tangible organisational benefits. Reduced fatigue and discomfort allow workers to sustain task performance, while lower injury rates translate into fewer lost workdays and reduced compensation costs.

From a management perspective, benefits include:

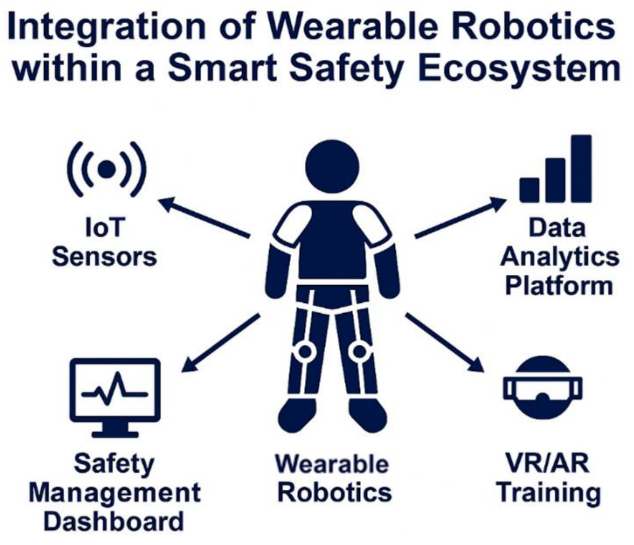
- Reduction in operating costs related to injuries
- Improved workforce retention and morale
- Enhanced safety culture and compliance
- Lower training and retraining expenses

For workers, wearable robotics provide increased comfort, reduced risk of chronic pain and extended working ability, which are particularly important in aging workforces.

2.8 Integration with Smart Safety and Assistive Technologies

Wearable robotics achieve their greatest impact when integrated with other assistive and smart technologies. When combined with IoT- based monitoring, ergonomic data analytics and VR/AR training platforms.

It can evaluate risk exposure, optimise device deployment and continuously improve safety strategies. Integration enables **evidence-based decision-making**, personalised assistance and scalable safety management.



2.9 Summary and Outlook

Wearable robotics and exoskeleton solutions are evolving from standalone technologies into **core components of modern occupational safety systems**. Through passive and active designs, region- specific assistance and compatibility with digital platforms, these solutions address long- standing challenges related to physical workload and musculoskeletal health.

As technology matures and adoption expands, wearable robotics are expected to play an increasingly central role in building **human- centric, productive and sustainable workplaces**, supporting both worker well- being and organisational performance.

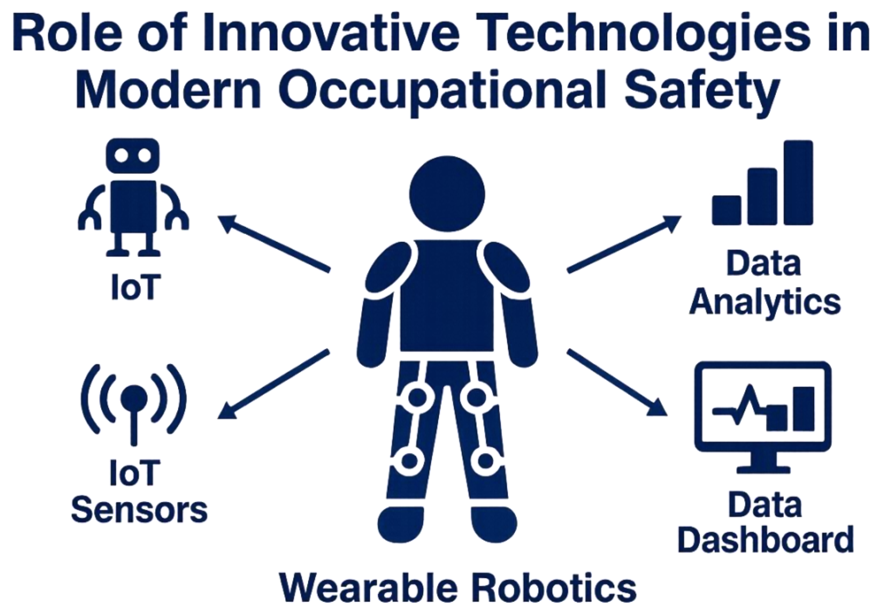
BENEFITS AND CHALLENGES OF INNOVATIVE TECHNOLOGIES

Chapter 3 – Benefits and Challenges of Innovative Technologies

3.1 Introduction

Innovative technologies, such as wearable robotics, exoskeleton solutions, Internet of Things (IoT), Artificial Intelligence (AI) and digital safety platforms are increasingly deployed to address long-standing occupational safety and health (OSH) challenges. These technologies can effectively reduce workplace accidents, minimise physical strain, improve risk visibility and enhance overall safety performance. Notwithstanding these benefits, they present new technical, regulatory, organisational and human-factor challenges that must be managed carefully.

As highlighted by recent exoskeleton technology developments and robotic safety standards, innovation alone does not automatically translate into safer and healthier workplaces. Effective deployment requires a balanced understanding of **what these technologies can achieve, what are the potential risks and how regulatory and functional safety frameworks can guide their responsible use**. This chapter examines the key benefits and challenges associated with innovative technologies in OSH, with particular attention to wearable robotics and robotic systems operating in close proximity to people.



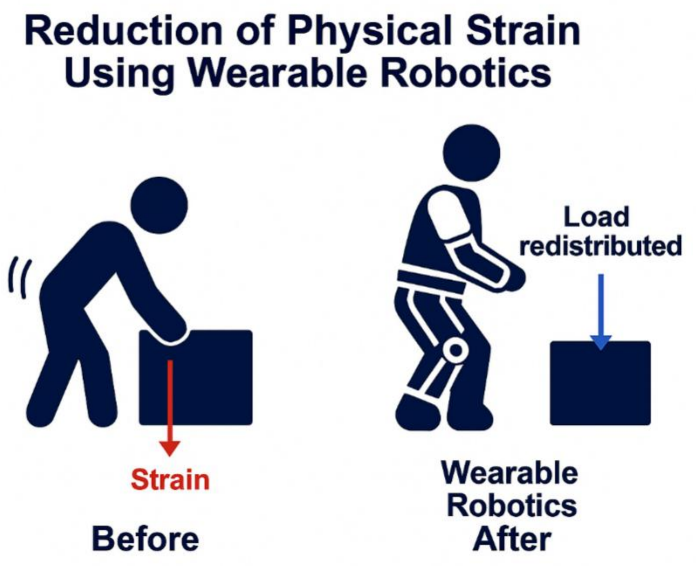
3.2 Benefits of Innovative Technologies in Occupational Safety and Health

3.2.1 Reduction of Physical Strain and Musculoskeletal Disorders

One of the most direct benefits of wearable robotics and exoskeleton solutions is their ability to reduce physical strain on workers. Work-related musculoskeletal disorders (WMSDs), particularly affecting the lower back, shoulders, neck and lower limbs, remain among the leading causes of occupational injury and long-term disability.

Wearable exoskeletons reduce biomechanical load by redistributing forces away from vulnerable joints and muscle groups. Passive and active exoskeleton solutions are now capable of supporting lifting, bending, overhead work, walking and prolonged standing. Studies conducted in healthcare and industrial settings show that exoskeleton use can significantly reduce muscle activation and perceived exertion during physically demanding tasks. This reduction directly contributes to lower injury risk, delayed fatigue onset and improved worker endurance.

Looking through the lens of an organisation, fewer musculoskeletal injuries mean reduced absenteeism, lower compensation costs and greater workforce sustainability, especially in aging societies where physical capacity naturally declines.

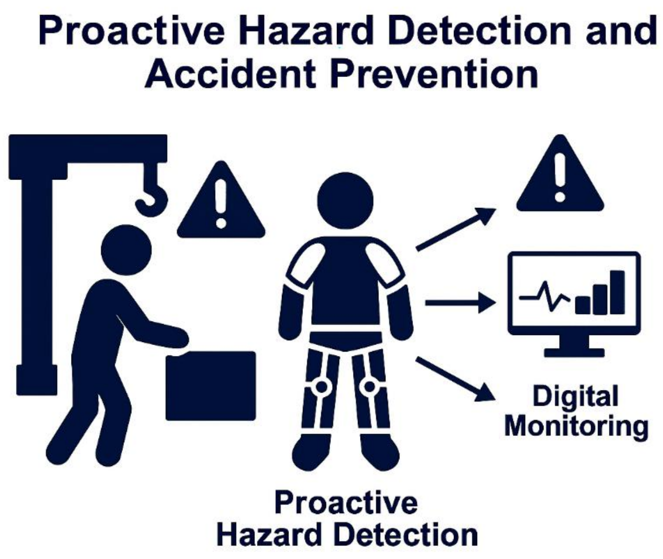


3.2.2 Enhanced Hazard Awareness and Accident Prevention

Innovative technologies like IoT sensors, AI-based analytics and real-time monitoring platforms provide unprecedented visibility into workplace hazards. Rather than relying solely on periodic safety inspections or manual supervision, organisations can now monitor environmental conditions, worker posture, equipment status and operational risks continuously.

For example, connected sensors can detect unsafe proximity between workers and machinery, abnormal vibrations, excessive loads or deviations from safe operating parameters. When combined with analytics platforms, these data streams enable early warnings and proactive interventions before accidents occur. This shift from reactive to preventive safety management represents a fundamental improvement in how OSH risks are addressed.

In autonomous and robotic systems, safety-rated monitoring functions—such as speed control, emergency stop mechanisms and obstacle detection—play a critical role in preventing collisions and unintended hazardous behaviour.



3.2.3 Improved Task Consistency, Productivity and Quality

Innovative technologies not only improve safety but also enhance operational consistency and productivity. Robotics and automation systems can perform repetitive, hazardous or precision-critical tasks with great reliability, reducing human exposure to danger while maintaining consistent performance.

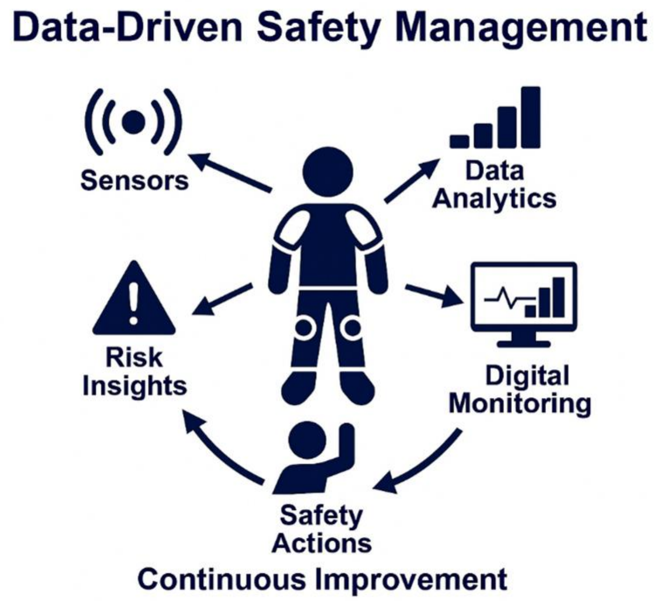
Wearable robotics contribute to productivity by enabling workers to perform physically demanding tasks with less fatigue and greater comfort. Improved posture and reduced pain allow workers to maintain focus and task quality over longer periods. In healthcare, for example, exoskeletons can support safe patient handling while preserving caregiver efficiency and care quality.

Together, these technologies serve the dual purpose of **safety and productivity**, challenging the traditional misconception that safety improvements will inevitably reduce output or increase cost.

3.2.4 Data-Driven Safety Management and Continuous Improvement

Another key benefit lies in the ability to collect and analyse large volumes of safety-related data. Innovative technology and advanced systems generate insights into accident patterns, ergonomic risks, system performance and user behaviour. These insights support evidence-based decision-making, targeted interventions and continuous improvement of safety measures.

In regulated environments, robust data gathering also makes it easier to comply with safety standards and regulatory requirements for compliance, traceability and documentation. Digital records of risk assessments, testing results and safety function performance help organisations demonstrate due diligence and accountability.



3.3 Challenges of Implementing Innovative Safety Technologies

Despite clear benefits, the adoption of innovative technologies presents multiple challenges that must be addressed to ensure safe, effective and sustainable deployment.

3.3.1 Technical Complexity and System Reliability

Modern safety technologies — including exoskeletons, collaborative robots, autonomous systems and AI systems — are technically complex. They incorporate mechanical structures, electronic components, software, sensors, batteries and communication modules. Each component introduces potential failure modes.

Robust engineering, testing and validation are essential to ensure that systems behave safely under all operating conditions. Functional safety principles emphasise that safety- related functions must remain reliable even in the presence of hardware faults, software errors or unexpected inputs. Failure to properly design and validate these systems can pose new risks rather than mitigating existing ones.

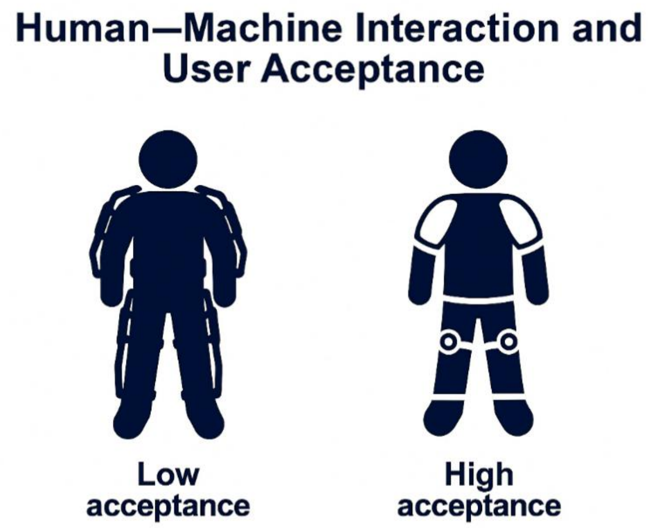
For wearable robotics, additional complexity arises from variability in human movement, body size, behaviour and misuse scenarios. Designing systems that are both adaptive and fail- safe is a significant engineering challenge.

3.3.2 Human–Machine Interaction and User Acceptance

Technologies that operate in direct contact with people must account for human factors. Wearability, comfort, usability and predictability strongly influence whether workers accept or reject new safety solutions.

If exoskeletons are uncomfortable, restrictive or perceived as intrusive, workers may choose not to use them or may use them incorrectly. Similarly, autonomous and AI systems that behave unpredictably can erode trust and create anxiety among workers operating nearby.

Human- machine interaction must therefore be intuitive, transparent and predictable. Safety standards increasingly emphasise the importance of behaviour predictability, clear warnings and understandable system responses, especially for robots operating alongside humans in shared spaces.



3.3.3 Regulatory and Functional Safety Compliance

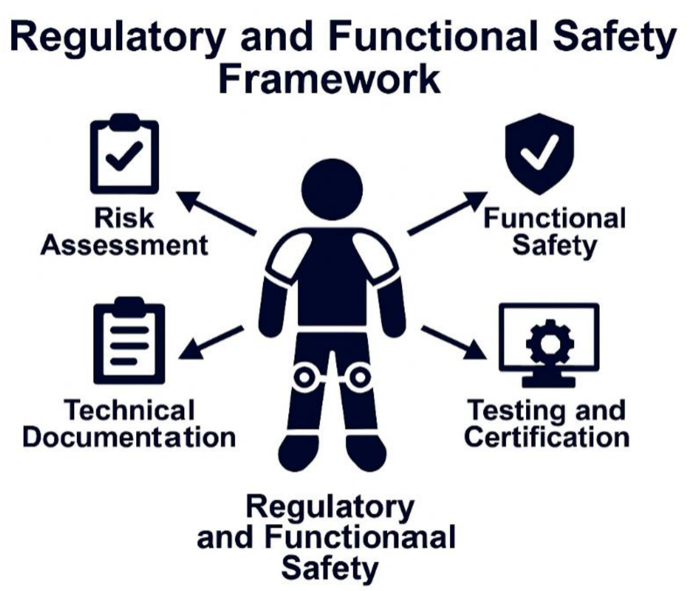
A major challenge in deploying wearable robotics and robotic technologies is navigating complex regulatory landscapes. Products must comply with applicable international and regional regulations governing machinery safety, electrical safety, electromagnetic compatibility (EMC), functional safety and — in some cases — cybersecurity and Artificial Intelligence (AI).

In Europe, for example, robotic systems are subject to machinery regulations that require formal risk assessment, hazard mitigation and conformity documentation. Functional safety standards specify how safety- related control systems must be designed, analysed and validated to achieve defined performance levels.

For organisations, compliance requires:

- Clear identification of target markets
- Comprehensive risk assessment across the full product lifecycle
- Verification and validation of safety functions
- Proper technical documentation and user instructions

These requirements demand specialised expertise and resources, particularly for small and medium- sized enterprises adopting advanced technologies.

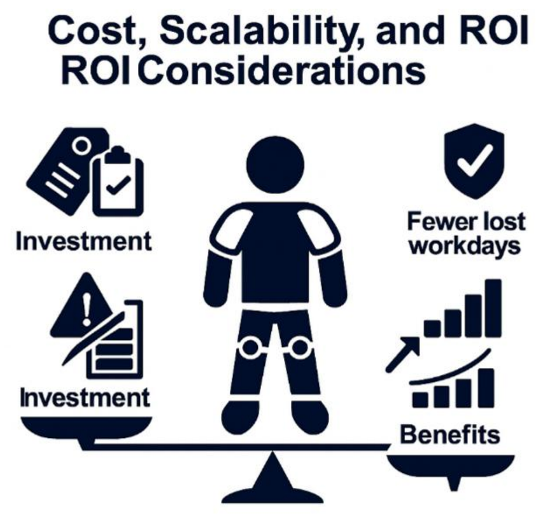


3.3.4 Cost, Scalability and Return on Investment

While innovative technologies promise long- term benefits, initial investment costs can be substantial. Exoskeletons, robotics systems, testing, certification, training and infrastructure upgrades all contribute to upfront expenditure.

Cost considerations are especially important where adoption is intended at scale. Organisations must balance technology performance with affordability and maintainability. In the context of wearable robotics, lighter, passive or soft exosuit designs are increasingly favoured because they can deliver meaningful safety benefits at lower cost and reduced complexity.

Demonstrating Return on Investment (ROI) — through reduced injuries, fewer lost workdays and improved productivity — is essential for sustained adoption.



3.3.5 Cybersecurity and Data Protection

As safety systems become increasingly connected, cybersecurity emerges as a new dimension of occupational safety. Unauthorised access, data manipulation or system disruption can compromise safety- critical functions and pose new hazards to wearable robotics and robotic technologies.

Increasingly, modern regulatory frameworks are recognising cybersecurity as an integral part of overall system safety, particularly for connected robotic systems and IoT platforms. Organisations and businesses must give due consideration to secure system design, software updates, access control and data protection throughout the system lifecycle.

3.4 Addressing Challenges through Standards, Design and Governance

Many of the challenges associated with innovative technologies can be mitigated through thoughtful design, standards adherence and strong governance. International safety standards provide structured methodologies for:

- Risk assessment and risk reduction
- Functional safety analysis
- Validation of safety- related control systems
- Management of human- machine interaction risks

By integrating safety considerations from the earliest design stages and addressing the full lifecycle from installation to operation and decommissioning, organisations and businesses can ensure that technology adoption enhances rather than undermines workplace safety. Cross- disciplinary collaboration among engineers, safety professionals, regulators and end users is critical. Training and change management further support safe and effective implementation.

3.5 Conclusion: Balancing Innovation and Safety

Innovative technologies like wearable robotics, exoskeleton solutions, Internet of Things (IoT), Artificial Intelligence (AI) and digital safety platforms offer powerful tools that tackle occupational safety and health challenges. Their benefits include reduced physical strain, enhanced hazard awareness, improved productivity and data-driven safety management. However, these benefits can only be realised when technical, human, regulatory and organisational challenges are addressed systematically.

A balanced approach that combines innovation with rigorous safety engineering, regulatory compliance and human-centric design is essential. When implemented responsibly, innovative technologies can play a transformative role in reducing workplace accidents and creating safer, healthier and more sustainable work environments.

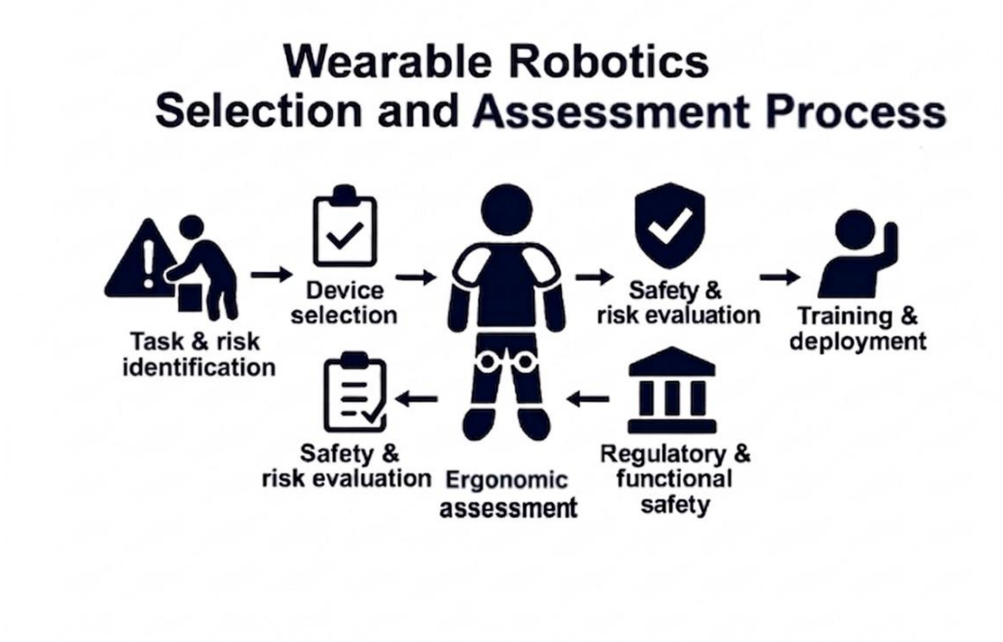
GUIDANCE ON SELECTING THE APPROPRIATE WEARABLE ROBOTIC DEVICE AND THE ASSESSMENT PROCESS AND CRITERIA FOR DETERMINING SUITABILITY

Chapter 4 – Guidance on Selecting the Appropriate Wearable Robotic Device and the Assessment Process and Criteria for Determining Suitability

4.1 Introduction

As wearable robotic devices and exoskeleton solutions move from pilot trials to routine workplace deployment, organisations must adopt a structured approach to device selection and suitability assessment. While wearable robotics offer clear benefits in reducing physical strain, improving posture and preventing work-related musculoskeletal disorders (WMSDs), improper selection or implementation can limit effectiveness and introduce new risks.

This chapter provides **step-by-step guidance** on selecting appropriate wearable robotic devices and outlines an **assessment framework and criteria** for determining suitability for specific occupational tasks, workplaces and user groups. The guidance integrates technological considerations, ergonomics, safety principles and regulatory expectations to support informed and responsible adoption of wearable robotic devices.



4.2 Step 1 – Understanding Task-Specific Occupational Risks

The starting point for selecting a wearable robotic device is a **clear understanding of the occupational safety and health problem to be addressed**. Wearable robotics are task-specific solutions; they are most effective when matched to clearly defined risk factors.

Key questions to consider include:

- Which tasks involve **manual handling, lifting, bending, twisting, prolonged standing or overhead work**?
- Which body regions are most affected (e.g. lower back, shoulders, knees, wrists)?
- Are the risks **acute** (injury during a single task) or **cumulative** (fatigue or chronic disorders over time)?
- How frequently and for how long are these tasks performed?

For example:

- Repetitive bending and lifting tasks point toward **back and trunk exoskeletons**
- Prolonged overhead work suggests **shoulder and upper-limb exoskeletons**
- Extended walking, standing or squatting may benefit from **lower-limb assistance**

A task-based risk analysis ensures that wearable robotics are applied as **targeted preventive measures**, rather than as generic equipment.

4.3 Step 2 – Selecting the Appropriate Type of Wearable Robotic Device

4.3.1 Active vs Passive Exoskeletons

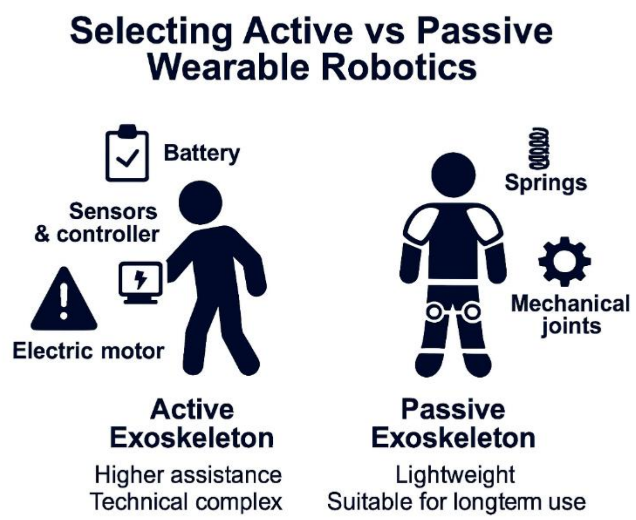
One of the most fundamental selection decisions is whether to use an **active (powered)** or **passive (non-powered)** wearable robotic device.

- **Active exoskeletons** provide higher levels of assistance through motors or actuators and are typically used in rehabilitation or specialised applications.
- **Passive exoskeletons** rely on mechanical elements like springs, elastic components or cables to redistribute forces and store energy.

For most occupational safety applications, **passive exoskeletons are preferred** for the following advantages:

- Lower weight and complexity
- No reliance on batteries or motors
- Easier maintenance
- Intrinsic safety and predictability
- Greater suitability for long daily use

Active exoskeletons may be considered where substantial assistance is required, but they demand more rigorous safety assessment and operational control.

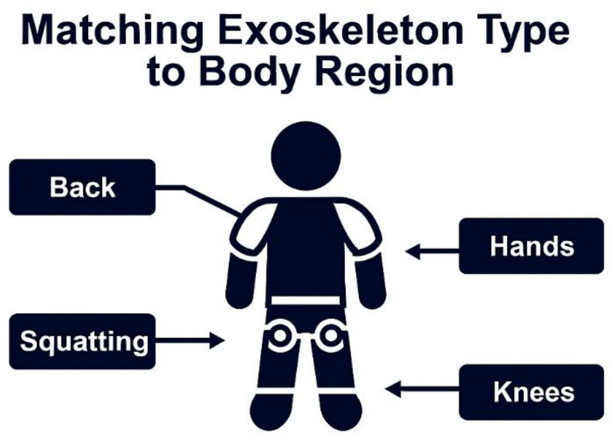


4.3.2 Matching Device Design to Body Region

Wearable robotic devices are designed to protect and support specific body regions. Selection should align with results of task assessments:

- **Back and trunk exoskeletons**: Suitable for lifting, bending and handling tasks; reduce lumbar loading
- **Shoulder exoskeletons**: Designed for overhead and arm-elevation tasks; reduce shoulder fatigue
- **Lower-limb exoskeletons**: Assist walking, squatting and standing; reduce knee and hip strain
- **Hand and grip assist devices**: Suitable for repetitive grasping or tool-intensive tasks

Selecting an excessively complicated or mismatched device can reduce user acceptance and limit safety benefits.



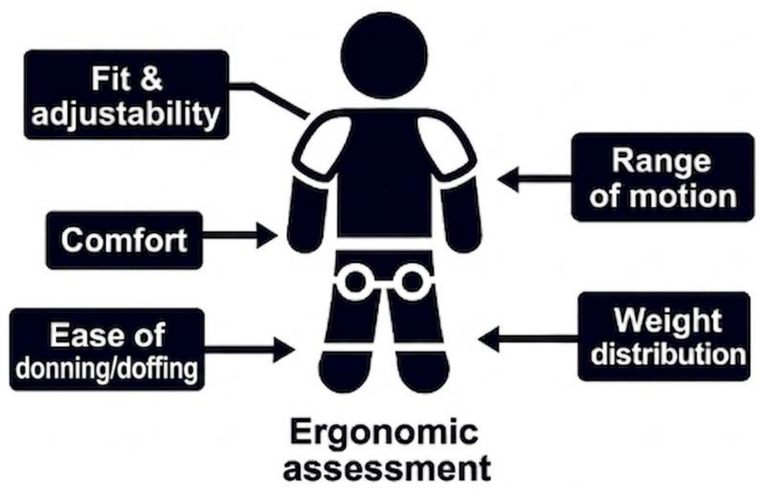
4.4 Step 3 – Ergonomic and Human-Factor Assessment

Human factors play a critical role in determining whether a wearable robotic device will be used correctly and consistently.

Key ergonomic considerations include:

- **Fit and adjustability**: The device must accommodate different body sizes and shapes
- **Comfort and pressure distribution**: Prolonged discomfort increases rejection risk
- **Range of motion**: The device should support natural movement rather than impede it
- **Ease of donning and doffing**: Devices should be quick and easy to put on and remove
- **Weight distribution**: Excessive weight or imbalance increases fatigue

Field experience shows that even technically effective exoskeletons may fail if workers perceive them as uncomfortable, restrictive or intrusive. User trials, feedback sessions and pilot deployment are therefore essential components of suitability assessment.



4.5 Step 4 – Safety and Risk Assessment

Wearable robotic devices are safety-related equipment and must be assessed accordingly. A **structured risk assessment** should be conducted before deployment, considering the entire lifecycle of the device.

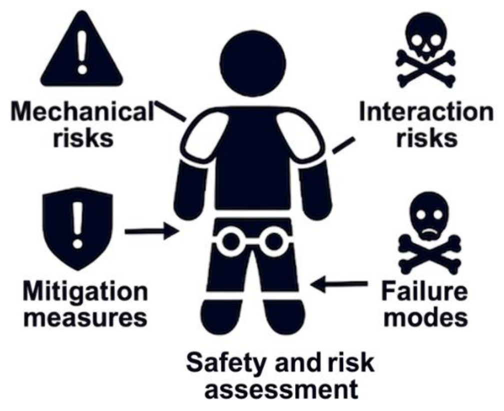
Key risk assessment elements include:

- **Mechanical risks**: Pinch points, sharp edges, joint misalignment
- **Operational risks**: Slips, trips, interference with other PPE or tools
- **Human-machine interaction risks**: Unintended forces, delayed response, misuse
- **Failure modes**: Device malfunction, wear and tear, incorrect adjustment

Viable risk mitigation measures:

- Design safeguards
- Usage restrictions
- Clear operating instructions
- Training and supervision

The risk assessment process should align with recognised safety principles, focusing on hazard identification, risk estimation and mitigation instead of assuming inherent safety.



4.6 Step 5 – Regulatory and Functional Safety Considerations

Selecting a wearable robotic device also requires attention to **regulatory compliance and functional safety expectations**. While requirements differ across regions, common expectations include:

- **Documented risk assessment**
- **Clear intended use and limitations**
- **Technical documentation and user manuals**
- **Verification and testing against applicable standards**
- **Traceability of safety-critical components**

Additional considerations for connected or powered devices:

- Electrical safety
- Electromagnetic compatibility
- Battery and charging safety
- Cybersecurity for connected systems

Organisations should work with suppliers, laboratories and certification bodies who are familiar with applicable regulatory frameworks and capable of providing appropriate documentation and support.

<u>International Standards Relevant to Wearable Robotic Devices</u>

Requirements	Key International Standards	Scope and Relevance to Wearable Robotics
Electrical Safety	IEC 60335-1	Provides baseline electrical safety requirements applicable to electrically powered wearable devices and supporting equipment.
	IEC 60601-1	Relevant for medical and rehabilitative exoskeletons used in healthcare environments.
Electromagnetic Compatibility (EMC)	IEC 61000-6-1 / IEC 61000-6-2	Ensures wearable robotic devices remain safe and functional when exposed to electromagnetic disturbances.
	IEC 61000-6-3 / IEC 61000-6-4	Limits electromagnetic emissions to prevent interference with other equipment.

	IEC 60601-1-2	International collateral standard for Electromagnetic Disturbances (EMC) specifically for Medical Electrical Equipment and systems.
Battery and Charging Safety	IEC 62133- 2	Core safety standard for lithium- based batteries used in wearable robotics.
	IEC 62619	Relevant for higher- capacity battery systems used in occupational wearable devices.
	IEC 60335-2-29	Applies to charging systems and docking stations for wearable robotics.
Cybersecurity for Connected Systems	IEC 62443 series	Widely used framework for securing connected industrial and robotic systems against cyber threats.
	ISO/IEC 27001	Provides organisational governance for managing cybersecurity risks associated with connected wearable systems.
	UL 2900 series	Addresses software vulnerabilities, authentication and secure update mechanisms.
	EU Cyber Resilience Act (CRA) (regulatory framework)	Emerging regulatory requirement for products with digital elements, emphasising cybersecurity across the product lifecycle.

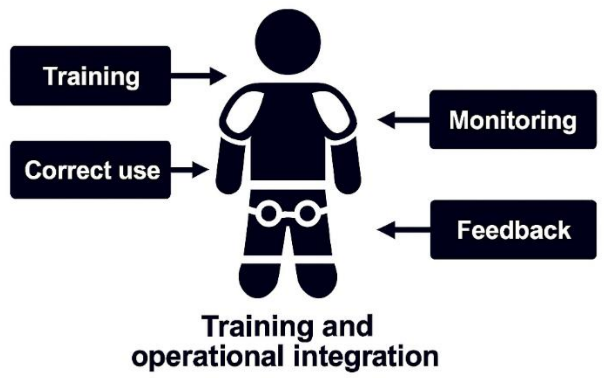
4.7 Step 6 – Training, Operational Integration and Monitoring

Even well- selected wearable robotic devices require proper **training and integration** to deliver safety benefits.

Key elements:

- User training on correct fitting, adjustment and usage
- Clear guidance on proper and improper use of the device
- Integration with existing PPE, work procedures and safety rules
- Ongoing monitoring to verify correct use and identify emerging issues

Regular evaluation of effectiveness — such as reduced fatigue, fewer injuries or improved task comfort — helps organisations determine whether the selected solution remains appropriate.

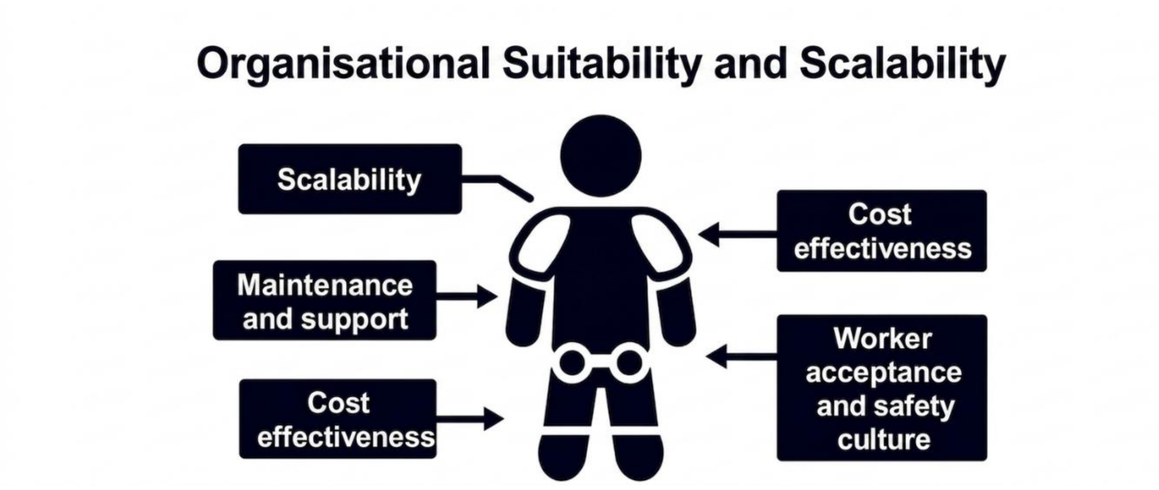


4.8 Step 7 – Organisational Suitability and Scalability

Beyond technical suitability, organisations should consider:

- **Scalability**: Can the solution be deployed across teams or sites?
- **Maintenance and support**: Are spare parts, servicing and adjustments manageable?
- **Cost-effectiveness**: Do benefits justify investment?
- **Worker acceptance and safety culture**: Is the organisation ready for wearable technologies?

Organisations should opt for gradual roll-out through pilot projects to refine selection criteria and build internal experience.



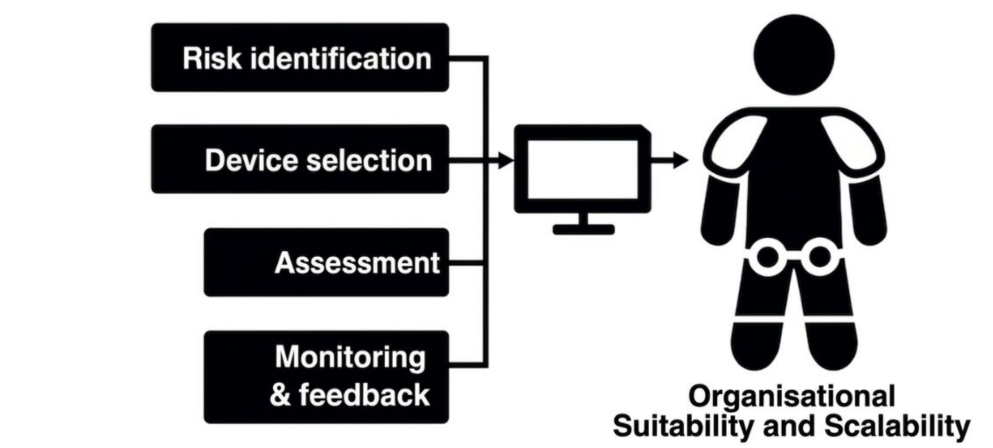
4.9 Summary and Key Takeaways

Selecting the appropriate wearable robotic device requires more than choosing a product — it demands a **systematic assessment process** that integrates task analysis, ergonomics, safety, regulation and organisational readiness.

Key principles include:

- Start with **task-specific risk identification**
- Match device type and body region to real ergonomic needs
- Prioritise ergonomics and user acceptance
- Conduct structured safety and risk assessments
- Ensure regulatory and functional safety alignment
- Support deployment with training and monitoring

When selected and implemented thoughtfully, wearable robotics can become effective, accepted and sustainable tools for reducing workplace accidents and improving occupational safety and health.



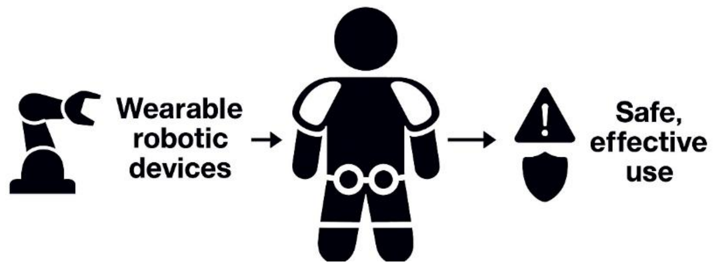
RECOMMENDATIONS FOR FITTING AND TRAINING OF WEARABLE ROBOTIC DEVICES FOR INDIVIDUAL USERS

Chapter 5 – Recommendations for Fitting and Training of Wearable Robotic Devices for Individual Users

5.1 Introduction

The effectiveness of wearable robotic devices and exoskeleton solutions depends not only on their technical capabilities, but also on how well they are **fitted to the user's body** and how safely and correctly they are **used in real working environments**. Improper fitting or inadequate training may reduce benefits, limit user acceptance or introduce new safety risks. Conversely, well- fitted devices combined with structured training can significantly reduce physical strain, enhance work performance and improve workplace safety outcomes.

This chapter provides **practical recommendations** on fitting wearable robotic devices to individual users and establishing **training and practice regimes** that support safe, effective and sustainable use. This guidance is applicable across a wide range of industries, including construction, manufacturing, logistics, healthcare and facility management.



5.2 Individual Fitting and Adjustment of Wearable Robotic Devices

5.2.1 Importance of Proper Fitting

Wearable robotic devices interface directly with the human body. Unlike tools or machines that operate at a distance, exoskeletons transfer forces through contact points, such as the shoulders, back, hips, legs or arms. Therefore, proper fitting is essential to ensure:

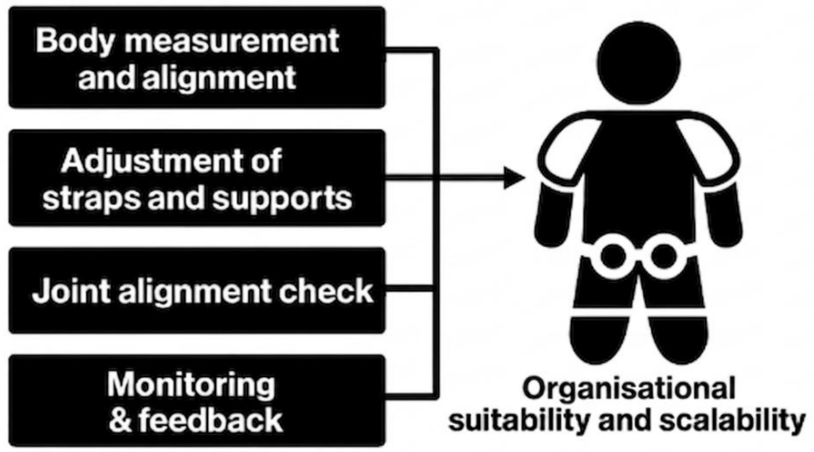
- Effective load redistribution
- Correct alignment with joints
- User comfort during prolonged use
- Prevention of unintended pressure or movement restriction

Poorly fitted devices may cause discomfort, reduce mobility or increase fatigue, undermining both safety and productivity.

5.2.2 Initial Fitting Procedure

Before first use, each user should undergo a structured fitting process conducted by trained personnel. Recommended steps include:

1. **Body measurement and alignment**
   Key body dimensions, such as height, limb length, waist circumference and joint locations, should be identified to ensure accurate alignment between the device and the user's anatomy.
2. **Adjustment of straps and supports**
   Straps, belts and fasteners should be adjusted to provide secure support while avoiding excessive tightness. Pressure should be evenly distributed across contact areas.
3. **Joint alignment check**
   Mechanical joints or soft assistance pathways should align with the user's natural joint centres to avoid abnormal motion or shear forces.
4. **Initial movement test**
   Users should perform basic movements — walking, bending, arm elevation or sit-to-stand — to confirm that the device supports, rather than restricts, natural motion.



5.2.3 Comfort and Wearability Evaluation

Comfort is a critical determinant of long-term use and acceptance. Even technically effective devices may be rejected if they cause discomfort. Users should be encouraged to provide feedback during fitting, focusing on:

- Pressure points or pinching
- Heat and breathability
- Weight distribution
- Ease of movement

Minor adjustments can often resolve discomfort and significantly improve acceptance.

5.3 Training for Safe and Effective Use

5.3.1 Structured User Training

All users should receive **formal training** before regular use of wearable robotic devices or exoskeleton solutions. Clear understanding reduces misuse and builds user confidence. Training should be proportionate to device complexity and task criticality. It typically includes:

- **Device overview**
  Purpose, key components and intended use of the device.
- **Correct donning and doffing**
  Step- by- step instruction on putting on and removing the device safely and efficiently.
- **Operating principles**
  Explanation of how the device provides assistance (e.g. passive load redistribution or active support) and its limitations.
- **Do's and Don'ts**
  Situations where the device should or should not be used, including task boundaries and environmental constraints.

5.3.2 Task- Specific Practice

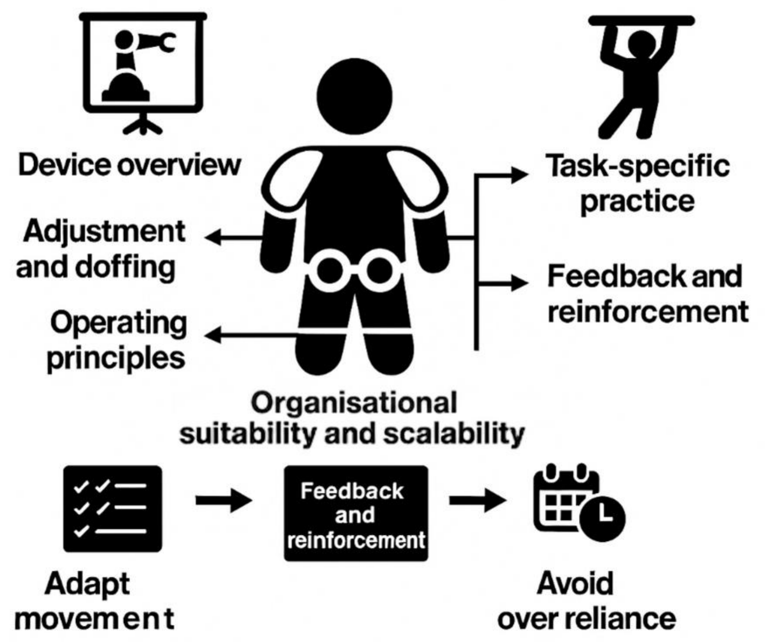
Beyond general instructions, users should practice using wearable robotic devices in **actual or simulated work tasks**, such as lifting, overhead installation, patient transfer or prolonged standing. Supervised practice allows users to:

- Adapt movement patterns gradually
- Learn how much support the device provides
- Avoid over- reliance or incorrect posture

This approach is particularly important for devices that interact dynamically with movement, such as lower- limb or upper- limb exoskeletons.

5.3.3 Progressive Familiarisation

It may take some time for users to adapt to wearable assistance. Short initial usage periods followed by gradual increase in duration can reduce fatigue and improve comfort. Progressive familiarisation also helps identify early issues that can be corrected through refitting or additional training.



5.4 Practice, Monitoring and Continuous Improvement

5.4.1 Pilot Use and Supervised Deployment

Before large-scale adoption, organisations are encouraged to conduct **pilot deployments** with a small group of users. Ensure the following during this phase:

- Usage is monitored closely
- User feedback is systematically collected
- Training, fitting and procedures are adjusted as required

Pilot use allows organisations to refine their approach and reduce risks before wider rollout.

5.4.2 Monitoring During Regular Use

Once deployed, ongoing monitoring can ensure that devices continue to be used correctly. Monitoring can include:

- Periodic observation by supervisors
- Informal user feedback sessions
- Checks for wear and tear or misalignment

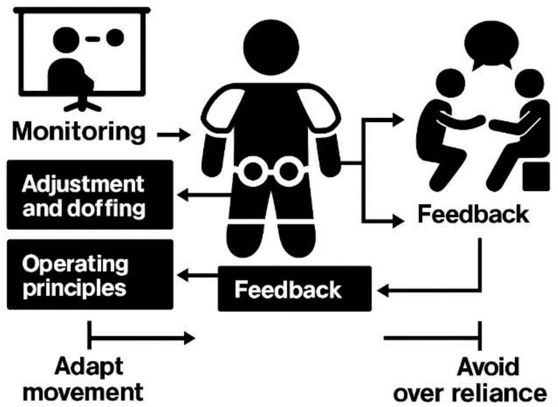
Monitoring should not focus solely on compliance, but also on identifying opportunities for improvement.

5.4.3 Feedback-Driven Refinement

User feedback is invaluable for improving safety and effectiveness. Organisations should establish channels for users to report:

- Comfort issues
- Interference with tasks
- Positive or negative impacts on fatigue or productivity

Feedback supports evidence-based decisions regarding device selection, training updates or procedural changes.



5.5 Training for Supervisors and Safety Personnel

Wearable robotics present new considerations for supervisors and safety staff. They should receive adequate training to support their roles:

- Understanding device functions and limitations
- Recognising incorrect use or poor fit
- Integrating wearable robotics into existing safety procedures
- Responding to incidents or user concerns

Informed supervisors play a key role in reinforcing safe practices and building trust in new technologies.

5.6 Integration with Workplace Safety Culture

Successful adoption of wearable robotics goes beyond individual training. Organisations should position these technologies as:

- **Preventive safety tools** as opposed to productivity surveillance devices
- **Supportive aids** as opposed to replacements for workers
- Part of a broader commitment to worker wellbeing and innovation

Open communication and involvement of workers in fitting, training and evaluation foster acceptance and positive safety culture.

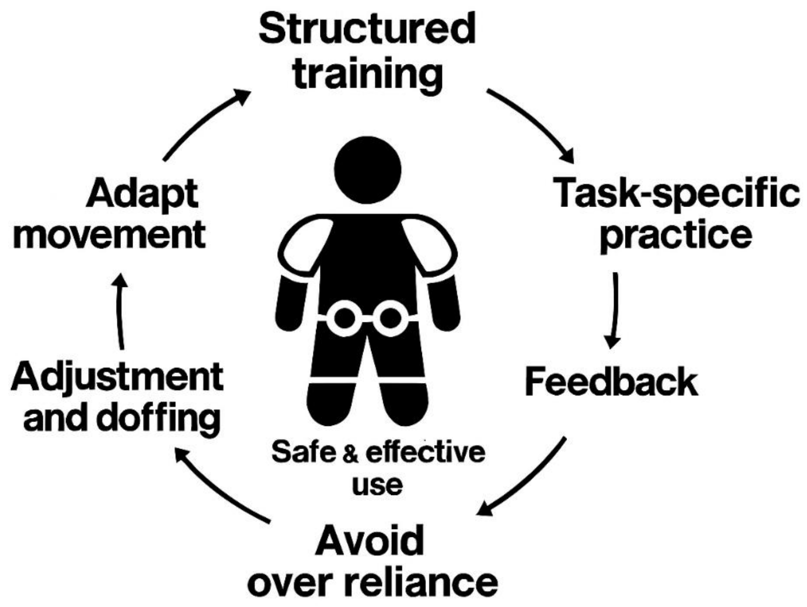
5.7 Key Recommendations and Good Practices

To ensure safe and effective use of wearable robotic devices, organisations should:

- Ensure individual fitting and comfort assessment before use
- Provide structured and task-specific training
- Encourage gradual familiarisation and supervised practice
- Implement pilot trials before large-scale deployment
- Monitor use and collect user feedback continuously
- Train supervisors and integrate devices into existing safety systems

5.8 Conclusion

Proper fitting, training and practice are essential to unlocking the full benefits of wearable robotic devices. When combined with structured training and continuous feedback, exoskeleton solutions can significantly reduce physical strain, improve safety and enhance productivity. By adopting a human-centric and evidence-based approach, organisations can ensure that wearable robotics are used safely, effectively and sustainably, contributing to healthier and more efficient workplaces.



GUIDANCE ON MAINTENANCE AND REPAIR OF WEARABLE ROBOTIC DEVICES

Chapter 6 – Guidance on Maintenance and Repair of Wearable Robotic Devices

6.1 Introduction

Proper maintenance and timely repair of wearable robotic devices and exoskeleton solutions are essential to ensure **safe operation, reliable performance and long service life**. As wearable robotics interact directly with the user's body during physically demanding tasks, degraded components or improper repairs may compromise both safety and effectiveness. This chapter provides practical guidance on routine maintenance, inspection, cleaning, storage and repair practices to support sustained and responsible use.

6.2 Importance of Maintenance for Safety and Performance

Wearable robotic devices rely on a combination of mechanical structures, textile components, fasteners, sensors and in some cases powered elements. Over time, normal wear, repeated movements and environmental exposure can lead to loosening, degradation or misalignment. Regular maintenance ensures that:

- Assistive forces remain predictable and effective
- Alignment with the user's body is maintained
- Discomfort, fatigue or injury risks are avoided
- Unexpected failures during operation are minimised

Rather than treating maintenance solely as a technical task, it should be **fully integrated into occupational safety management**. Maintenance should be carried out strictly in accordance with the device manufacturer's manuals and instructions.

6.3 Routine Inspection and Daily Checks

Before each use, users or supervisors should perform **basic visual and functional checks**, including:

- **Straps, belts and fasteners**
  Check for fraying, tearing, loose stitching or loss of elasticity.
- **Mechanical joints and connectors**
  Ensure smooth movement without excessive resistance, noise or instability.
- **Contact surfaces**
  Inspect padding and interface points for wear, deformation or contamination.
- **Fit and alignment**
  Confirm the device still fits correctly and has not shifted since the last use.

In the event of any abnormal findings, the device should be **temporarily withdrawn from use** until further inspection confirms safety.

6.4 Scheduled Maintenance and Servicing

Organisations should establish **periodic maintenance schedules** based on manufacturer guidance and usage intensity. Scheduled servicing may include:

- Detailed inspection of load-bearing components
- Replacement of consumable or high-wear parts
- Verification of alignment and mechanical integrity
- Functional testing to confirm proper assistive behaviour

Maintenance should be carried out by **trained personnel or authorised service providers**. All actions should be documented to support traceability and continuous improvement.

6.5 Cleaning and Hygiene Management

Given that wearable devices are worn close to the body and may be shared, proper cleaning supports hygiene, comfort and durability:

- Clean contact surfaces routinely using manufacturer-approved agents
- Avoid harsh chemicals or aggressive methods that may damage materials
- Ensure devices are completely dry before storage or reuse

Enhanced hygiene protocols are recommended for shared devices.

6.6 Repair and Troubleshooting

When faults, damage or abnormal behaviour are detected, users should **not attempt ad-hoc repairs**. The recommended approach is:

1. **Immediate isolation** of the device from service
2. **Problem identification** and documentation of symptoms
3. **Authorised repair** using approved parts and procedures
4. **Post-repair verification**, including fitting checks and functional testing

Unauthorised modifications may invalidate safety assurances and increase risk.

6.7 User Responsibilities and Reporting

Users contribute to device longevity and safety by:

- Promptly reporting discomfort, unusual behaviour or visible wear
- Avoiding misuse or operation outside intended tasks
- Following correct donning, doffing and storage procedures

Encourage open reporting supports early intervention and accident prevention.

6.8 Storage and Environmental Care

Proper storage protects devices when not in use. Devices should be stored:

- In clean, dry and well-ventilated areas
- Away from excessive heat, moisture or direct sunlight
- In a manner that avoids deformation or unnecessary loading

Correct storage reduces premature wear and extends service life.

6.9 Key Recommendations and Good Practice

To ensure proper functioning and longevity, organisations should:

- Integrate maintenance into safety management systems
- Perform routine checks and scheduled servicing
- Use only authorised repair methods and components
- Maintain clear maintenance and repair records
- Encourage user reporting and feedback
- Implement appropriate storage and hygiene practices

6.10 Conclusion

Regular maintenance and responsible repair are essential to sustaining the safety, effectiveness and acceptance of wearable robotic devices. When combined with proper fitting, structured training and continuous monitoring, good maintenance practices will ensure that wearable robotics remain a **reliable, safe and long-term solution** for reducing physical strain and supporting healthier and more efficient workplaces. Maintenance should be carried out strictly in accordance with the device manufacturer’s manuals and instructions.

SAFETY CONCERNS AND RISKS ASSOCIATED WITH THE USE OF WEARABLE ROBOTIC DEVICES

Chapter 7 – Safety Concerns and Risks Associated with the Use of Wearable Robotic Devices

7.1 Introduction

Wearable robotic devices and exoskeleton solutions offer significant benefits in reducing physical strain, preventing work-related musculoskeletal disorders and improving productivity. However, as these technologies operate in **direct physical contact with the human body**, they also introduce safety concerns that are unique from those associated with conventional tools or machinery. Understanding these risks and adopting appropriate mitigation strategies are essential for ensuring that wearable robotics enhance occupational safety rather than creating new hazards.

This chapter outlines the **main safety risks associated with wearable robotic devices** and provides **practical mitigation strategies**, drawing on principles of ergonomics, functional safety, human–machine interaction and operational governance.

7.2 Mechanical and Physical Interaction Risks

7.2.1 Joint Misalignment and Excessive Forces

Wearable robotic devices are often designed with mechanical joints or assistance pathways that interact closely with human joints. If these components do not align with the user's anatomy properly, it may lead to excessive shear forces, abnormal torque or restricted movement. Over time, this may cause discomfort, fatigue or even injury.

Mitigation strategies include:

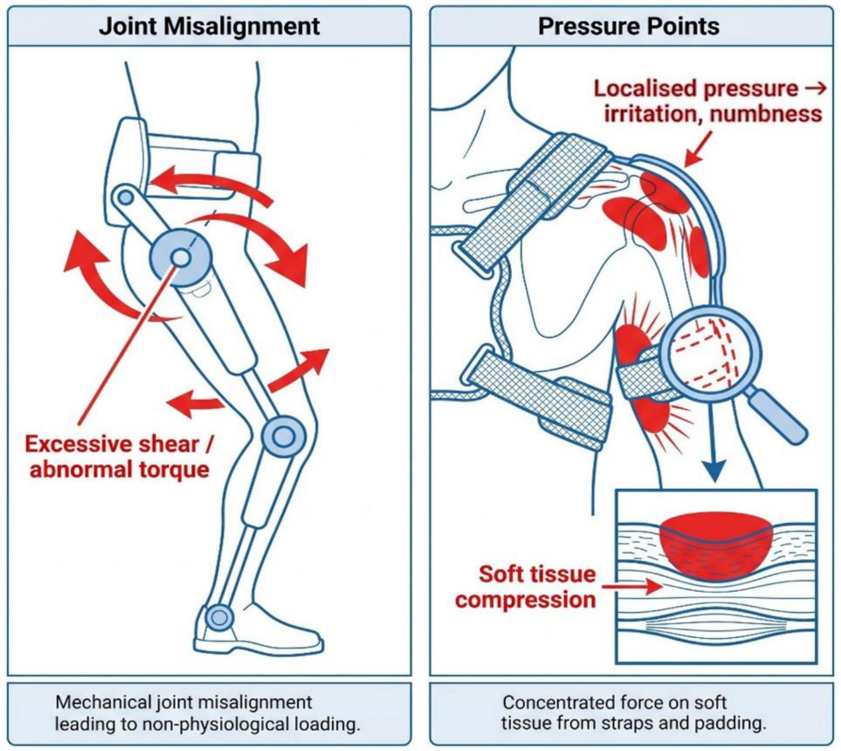
- Individual fitting and alignment checks before use
- Adjustable designs with multiple sizing and adjustment points
- Periodic reassessment of fit, especially when devices are shared among users

7.2.2 Pressure Points and Soft Tissue Stress

Contact surfaces, such as straps, pads and frames, may create localised pressure on soft tissues, particularly during prolonged use. Poorly distributed pressure can cause skin irritation, numbness or circulation issues.

Mitigation strategies include:

- Ergonomic design with compliant, breathable interface materials
- Comfort evaluation during initial fitting and pilot use
- Allowing gradual familiarisation to identify discomfort early



7.3 Operational and Task-Related Risks

7.3.1 Inappropriate Task Application

Wearable robotic assistance is not suitable for all tasks. Using a device outside its intended task scope — for example, during rapid movements, confined spaces or uneven terrain — may reduce stability or increase risk.

Mitigation strategies include:

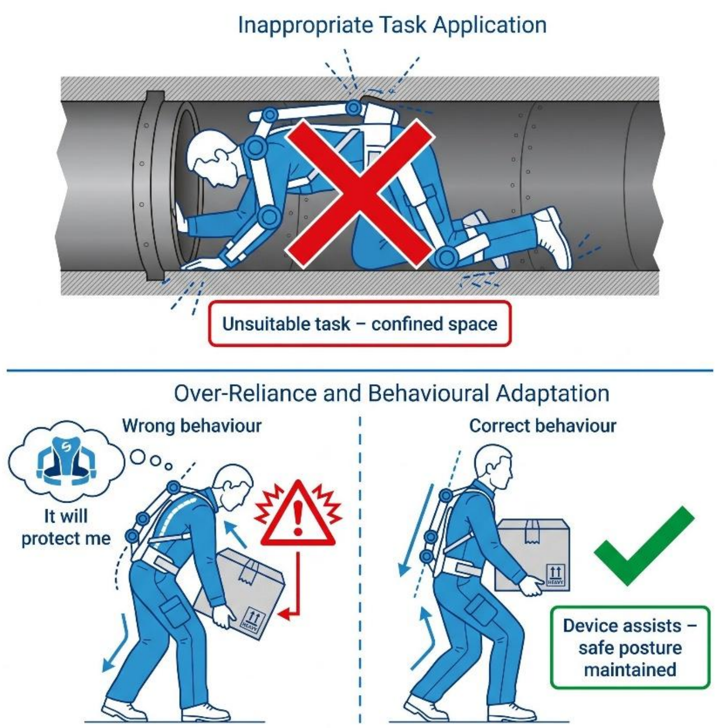
- Clear definition of intended tasks and limitations
- Training on "do's and don'ts" of device use
- Integration of wearable robotics into task-specific risk assessments

7.3.2 Over-Reliance and Behavioural Adaptation

A common concern is potential **over-reliance**, where users may adopt unsafe postures or reduce situational awareness because they expect the device to compensate. Over-reliance can undermine instead of promoting safe working behaviour.

Mitigation strategies include:

- Emphasising that wearable robotics are assistive tools, not replacements for safe working practices
- Structured training focusing on correct posture and movement
- Supervised practice and feedback to reinforce appropriate use



7.4 User-Related and Human-Factor Risks

7.4.1 Variability in User Capability and Acceptance

Users differ in physical strength, experience and comfort with technology. A device suitable for one user may be ineffective or uncomfortable for another, thus increasing the risk of misuse or rejection.

Mitigation strategies include:

- User-centric selection and fitting processes
- Pilot trials with representative user groups
- Incorporation of user feedback into device selection and deployment decisions

7.4.2 Fatigue and Cognitive Load

Although wearable robots aim to reduce physical strain, they may introduce initial cognitive demands as users adapt to assisted motion. Inadequate training can increase mental workload and distraction, particularly in complex environments.

Mitigation strategies include:

- Short initial usage periods for progressive familiarisation
- Task-specific practice under supervision
- Avoiding deployment in high-risk tasks until users demonstrate familiarity and confidence

7.5 Technical and Functional Safety Risks

7.5.1 Component Wear, Failure and Degradation

Mechanical components, textiles and fasteners are subject to wear over time. Undetected degradation can result in reduced assistance or unexpected behaviour.

Mitigation strategies include:

- Routine inspection and scheduled maintenance
- Clear maintenance and repair procedures
- Immediate removal from service when faults are detected

7.5.2 Powered and Connected Device Risks

Powered or connected wearable robotics may have additional risks that include electrical safety issues, battery faults, electromagnetic interference and cybersecurity vulnerabilities.

Mitigation strategies include:

- Compliance with applicable electrical, battery and EMC standards
- Controlled charging and storage practices
- Secure handling of connected systems and data, where applicable

7.6 Organisational and System-Level Risks

7.6.1 Inadequate Integration into Safety Management Systems

Deploying wearable robotics without integrating them into existing occupational safety and health frameworks may result in inconsistent practices, unclear responsibilities and unmanaged risks.

Mitigation strategies include:

- Aligning wearable robotics deployment with existing OSH policies
- Defining roles for users, supervisors and maintenance personnel
- Documenting procedures, training and maintenance activities

7.6.2 Insufficient Training and Supervision

Lack of training or ongoing supervision significantly increases the likelihood of misuse and unsafe adaptation.

Mitigation strategies include:

- Mandatory training before regular use
- Ongoing monitoring and refresher training
- Feedback mechanisms to support continuous improvement

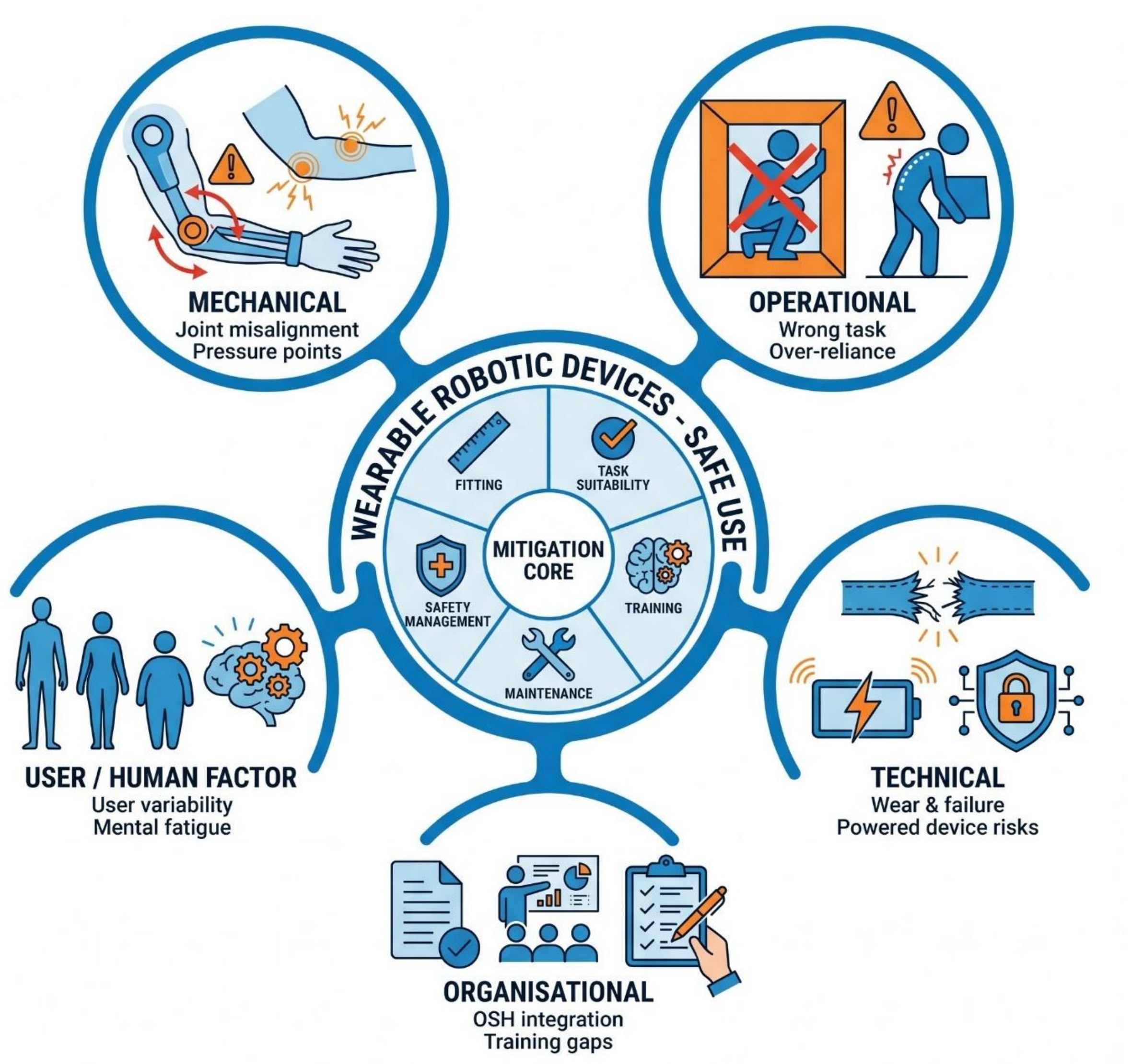
7.7 Summary of Key Risks and Mitigation Measures

The safe use of wearable robotic devices depends on recognising that **risk is multidimensional** — encompassing mechanical, human, operational, technical and organisational factors. For best results, mitigation strategies should feature:

- Proper fitting and ergonomic assessment
- Clear definition of task suitability and limitations
- Structured training, supervised practice and progressive familiarisation
- Routine inspection, maintenance and authorised repair
- Integration into organisational safety management systems

7.8 Conclusion

Wearable robotic devices have the potential to significantly improve occupational safety and health when applied responsibly. However, their close interaction with the human body requires a **systematic, risk-based approach** to safety. By identifying key risks and implementing targeted mitigation strategies, organisations can ensure that wearable robotics function as intended — supporting workers, reducing physical strain and contributing to safer, healthier and more efficient workplaces.



Safe use = Fitting + Task suitability + Training + Maintenance + OSH integration

Enquiry:

For enquiries regarding wearable robotics and exoskeleton solutions, please contact the Smart City Division of the Hong Kong Productivity Council at 2788 5098 or wtlam@hkpc.org.