Malaysian Journal of Medicine and Health Sciences (eISSN 2636-9346)

REVIEW ARTICLE

A Review on Ergonomics Factors Determining Working in Harmony with Exoskeletons

Isa Halim[1], Muhammad Nadzirul Izzat Mahadzir[1], Zulkeflee Abdullah[1], Muhammad Zaimi Zainal Abidin[1], Mohd Nazrin Muhammad[1], Adi Saptari[2]

[1] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
[2] Department of Industrial Engineering, President University, Jl. Ki Hajar Dewantara, Kota Jababeka, Cikarang Baru, Bekasi 17550, Indonesia.

ABSTRACT

Exoskeletons are wearable devices that can enhance human strength and are used in various fields, such as healthcare and the manufacturing industry. However, poorly designed exoskeletons can strain the muscles and cause injuries to users. The objectives of this review paper are to review the ergonomics factors that contribute to a harmonious user-exoskeleton interaction and to explore the current trends, challenges, and future directions for developing ergonomically designed exoskeletons. In this review, 102 relevant papers published from 2015 to 2023 were retrieved from Web of Science, Scopus, and Google Scholar. These papers were considered in the analysis for gathering relevant information on the topic. The authors identified six ergonomics factors, namely kinematic compatibility, contact pressure, postural control, metabolic cost, cognitive workload, as well as task demands and workplace conditions, that can influence the interaction between users and exoskeletons. By understanding and addressing these ergonomics factors during the design and development process, exoskeleton designers can enhance the user experience and adoption of the devices in daily living activities and industrial applications.
Malaysian Journal of Medicine and Health Sciences (2023) 19(6):311-327. doi:10.47836/mjmhs.19.6.41

Keywords: Ergonomics, Assistive device, Human-machine interaction, Exoskeleton technology

Corresponding Author:
Isa Halim, PhD
Email: isa@utem.edu.my
Tel: +606 2702615

INTRODUCTION

In the advancement of assistive device technology, exoskeletons are widely applied in many sectors, such as manufacturing and construction industries, healthcare and rehabilitation centers, and the military. Exoskeletons are mechanical devices worn by individuals to enhance or support their posture, movement, or physical activities (1). Exoskeletons are utilized by individuals from diverse professions, including industrial workers, healthcare professionals, gait trainers, and soldiers. Depending on the application, an exoskeleton will be attached to the entire body, lower body, upper body, specific body part, or specific joint. Exoskeletons are categorised according to the part of the body to which they are attached. For instance, a complete-body exoskeleton is a type of exoskeleton that is affixed to the entire human body. Exoskeleton can generally be divided into two categories: active and passive, as well as stiff and flexible structures (2,3). An active exoskeleton utilizes one or more actuators to enhance a user's strength and activate their bodily joints. Electric motors, hydraulic actuators, and active suspension control systems are examples of these actuators. Meanwhile, a passive exoskeleton consists of mechanical mechanisms such as springs, dampers, and pulleys, which does not require any actuator and power supply. A stiff-structure exoskeleton is constructed using rigid and hard materials, which can create contact stress and kinematic incompatibility for users. On the other hand, a flexible-structure exoskeleton, called an 'exosuit', is manufactured from soft materials that are lighter than a rigid exoskeleton (4).

Exoskeletons are widely utilized across various domains, particularly in industrial work processes like parts assembly and materials handling (5–20); healthcare and rehabilitation (21–28); elderly care for rehabilitation and daily activities such as sit-to-stand movement and walking (29,30); military (31,32); as well as sports and recreation (33,34). Using exoskeletons for industrial work processes has demonstrated several proven benefits, including a reduction in peak compression force in the back by 5 - 14% during manual lifting (35–37), lowering the perceived exertion and shoulder muscle activity during plastering jobs (38), and reducing the heart rate of 1.5 beats per minute in dynamic lifting tasks (39). This highlights the positive impact of exoskeletons on minimizing strain and potential injuries in such tasks. Additionally, the application of exoskeletons for industrial tasks showed promising results on work efficiency and productivity (40,41).

The primary objective of exoskeleton design is to customize the mechanical structure and software according to the users' physical characteristics, biomechanics, and cognitive abilities. This design principle is crucial for achieving optimal synchronization and harmonious interaction between users and exoskeletons, enabling smooth execution of body movements or specific tasks. A study pointed out that the design of the exoskeletons must be harmonious with the users' anatomy (42). "Harmony" means a situation in which the users are in a peaceful state with the exoskeletons, the tasks, and the work environment in which they can work together without mismatch or conflict. To be specific, harmony relationship between the user and exoskeleton can be seen in terms of kinematic compatibility (e.g. the exoskeleton's actuator is aligned with the human joint to allow smooth motion), minimal contact pressure between the human body and the exoskeleton, good postural controls, preserve metabolic cost, reducing cognitive workload, and friendly to task or workplace conditions. One of the ways to achieve this harmonious interaction is by considering ergonomics factors during the design and development stages of the exoskeletons. Ergonomics factors refer to the engineering principles that utilize theory, data, and design methodologies to ensure that an exoskeleton suits the needs, capabilities, and limitations of its users. Ergonomics factors play a crucial role in designing an effective and comfortable exoskeleton for the wearer. In other words, ergonomics is a scientific discipline that focuses on understanding interactions between humans and other system components (43). The main goal of ergonomics is to make sure that products, like exoskeletons, match or fit users' physical (e.g. kinematic/body motion), physiological (e.g. contractions of the muscles), psychological or cognitive (working memory), and behavioral needs. The application of ergonomics for enhancing occupational health and human well-being is well-established in many areas, such as manufacturing industry (44,45), healthcare sector (46), and agriculture (47).

This review aims to offer guidance to engineers and product designers about how to incorporate ergonomics factors into exoskeleton designs so that the devices can work well with the users. Neglecting ergonomics factors in designing and developing exoskeletons might pose a number of ergonomics risks while wearing the devices. As a result, poorly designed exoskeletons may force users to adopt unnatural movements, causing their brains to work overtime as they struggle to synchronize with the exoskeletons instead of achieving a harmonious interaction. In such cases, the users' bodies and the exoskeletons become incompatible, leading to inefficiency and potential discomfort or strain (48). Furthermore, weighty and inflexible-design exoskeletons can affect users' body motion and balance to perform tasks or exercises. These constraints can lead to ergonomics-related injuries such as muscle strain and sprain.

Based on recent review articles (49–74) in Table I, previous authors reviewed the following research interests related to exoskeleton technology, including: structural design, application and acceptance of exoskeletons in elderly care; design and application of exoskeletons for patient handling and rehabilitation; development and application of lower limb exoskeletons; application of artificial intelligence in exoskeleton development; mechanical design, sensors, and control systems; application of exoskeletons in manual handling tasks; physical human–exoskeleton interactions and critical factors influencing user experience in exoskeleton applications.

The authors observed that prior reviews mostly ignored the obvious lack of knowledge on ergonomics factors influencing operating in harmony with the exoskeletons. The exoskeleton applications and evolutions, hardware and software designs, as well as user acceptance of the exoskeletons, have been the subject of a sizable quantity of the published articles. However, a review on the ergonomics factors for achieving harmonious relationship between exoskeleton-user-task-workplace conditions appeared to be sparse. Therefore, this review aims to reveal the ergonomics factors determining harmonious interaction between the user-task-workplace in exoskeleton applications. Additionally, the authors discuss the current trends or strategies to achieve harmonious interaction corresponding to each ergonomics factor, challenges, and future research directions of ergonomic exoskeletons. The technical know-how presented in this paper is indeed useful to engineers and product designers in developing exoskeletons that are compatible with the physical and cognitive of users, tasks, and workplace conditions.

This paper is divided into two main sections that represent the results and discussion of the review. The results section reviews the six ergonomics factors, namely kinematic compatibility, contact pressure, postural control, metabolic cost, cognitive workload, as well as task demands and workplace conditions. These six ergonomics factors play a crucial role in achieving a harmonious interaction between users and exoskeletons, ultimately enhancing user experience and work performance. Meanwhile, the second section discusses the current trends or strategies to achieve harmonious exoskeleton-user interaction, challenges, and future research directions for ergonomic exoskeletons.

Table 1 – Focus of past review papers related to design and application of exoskeleton (2018-2023)

Review articles	Focus of review	Research interests
(49)	Joint types, actuation modes and controls of exoskeleton devices.	Design, application and acceptance of exoskeletons in elderly care.
(51)	Actuator and power supply, controls and mechanism design.	
(50)	Technology acceptance models.	
(52)	Methodologies to improve gait of older persons.	
(53)	Engineering design aspects of hip exoskeletons for gait rehabilitation and augmentation.	
(54)	Application of exoskeletons in patient handling tasks.	Design and application of exoskeletons for patient handling and rehabilitation.
(55)	Methodologies, metrics and experimental procedures to assess motor skills of lower limb exoskeletons usage.	
(56)	Application of lower limb rehabilitation exoskeleton for patients with lower limb disorders.	
(57)	Mechanical design and controls of rehabilitation exoskeleton.	
(58)	Development and innovation process of lower limb exoskeleton for rehabilitation purposes.	
(59)	Active hand exoskeleton for rehabilitation, assistance, augmentation, and haptic devices.	
(60)	Sensing and control of lower limb exoskeletons.	Development and application of lower limb exoskeletons.
(61)	Exoskeletons for lower limb applications, major research challenges and opportunities.	
(62)	Artificial intelligence-based upper limb exoskeletons.	Artificial intelligence (AI).
(63)	Recent developments in exoskeleton business and emerging applications such as artificial intelligence.	
(64)	The advances and trends of the processing and control systems based on artificial intelligence.	
(65)	Mechanical structure and actuation technologies of knee exoskeleton.	Mechanical design, sensors, and control systems.
(66)	Mechanical structure, performance metric, control systems, and actuators of exoskeletons.	
(67)	Development and challenges relating to control systems.	
(68)	Controller design (dynamic modelling and control system), and hardware system (actuator, transmission).	
(69)	Sensor technologies on normal and shear load for prosthetic, orthotic and exoskeleton applications.	
(70)	Actuation, structure, and interface attachments.	
(71)	Application of exoskeletons in manual handling tasks among Australian Defence Force personnel.	Exoskeleton application in manual materials handling tasks.
(72)	Exoskeleton technologies for manual handling tasks in construction.	
(73)	Metrics, testing procedures, and measurement devices used to assess human–exoskeleton interactions.	Physical human–exoskeleton interactions and user experience.
(74)	Factors influencing user experience in passive exoskeleton applications.	

METHODOLOGY

The research questions guiding this review are: What ergonomics factors enable the users to work in harmony with the exoskeletons? How to design exoskeletons for achieving harmonious interaction? The authors searched relevant journal papers, book chapters, and conference proceedings from electronic databases such as Web of Science, Scopus, and Google Scholar (n = 247), published from 2015 to 2023. These types of publications were excluded from the search: narrative papers without supporting data, Ph.D and Masters research theses, undergraduate final year reports, and textbooks. The search was conducted using the terms: 'exoskeleton', 'harmony interaction', 'ergonomics', 'industrial application', 'healthcare and rehabilitation', 'military', and 'sports'. The complete texts of English-language academic articles, including original research and reviews, were then downloaded. In order to gather additional pertinent articles, the authors also looked through all of the publications' reference lists. The review methodology procedure was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (75). There were 205 papers remained after screening the similar or overlap papers. Then, the authors examined and comprehended the title of these papers. Out of which, 79 papers were discriminated due to scope irrelevancy. Next, the abstract of 126 papers were read, and any paper with unclear abstract was eliminated (n = 15). The next step involved reading all 111 papers in their entirety. These papers will be considered for the final review if they satisfy the inclusion requirements. The requirements were: presenting research on the ergonomics of exoskeleton technology, kinematic compatibility, contact pressure, postural control, metabolic cost, cognitive workload, and task demands & workplace conditions. To reduce bias in the article selection process, the journal name, authors, and institution were taken into consideration as exclusion criteria. The quality of the selected papers was assessed by checking these requirements: Is the method applied in the studies reliable? Has the Institutional Review Board or Research Ethics Committee authorised the experimental protocols? Finally, 102 papers were chosen, reviewed, and mined for kinematic compatibility, contact pressure, postural control, metabolic cost, cognitive workload, as well as task demands and workplace conditions. A flowchart of the procedures used to gather, sort, and evaluate the published papers is shown in Fig. 1.

RESULTS

Kinematic Compatibility

Kinematics is about the motion of human limbs interconnected by the joints. When the mechanical components of the exoskeleton and human joints are

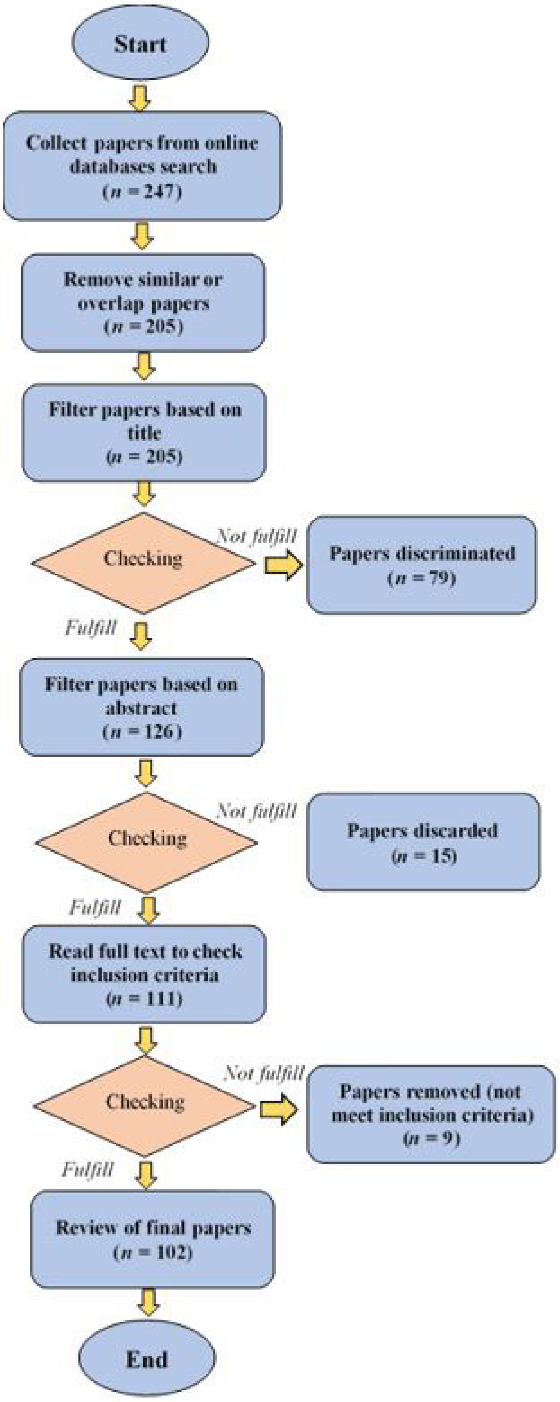

Figure 1: Flow of process in collecting, filtering and reviewing the papers

perfectly aligned, there is kinematic compatibility. In other words, there should be no mismatch or conflict between the exoskeleton's movement and the human limbs. A compatible design of the exoskeleton resulted in ease of user motion. Kinematic compatibility can be seen when the exoskeleton does not cause restrictions on the users' movements (76). One of the key requirements for kinematic compatibility is that the exoskeleton's mechanical components function simultaneously with the user's body parts. Hence, the dimension (especially the length and circumference) of the exoskeleton's structure should be measured and fabricated in a way that is fit to the user's body dimension. Additionally, the degree of freedom (DOF) of the exoskeleton and the user should likely be near to equal (77). These design elements are helpful in enhancing the user's physical performance in task manipulation and movement coordination.

On the other hand, exoskeletons that are designed without considering the kinematics of human body parts will pose issues such as limited or disrupted user movement, discomfort, and safety non-compliance such as snagging. Previous studies found that poor alignments between the user anatomical joints and the exoskeleton joints could create spurious forces and potentially deteriorate user performance (78,79). A study in (80) observed that the XoTrunk exoskeleton reduced the hip flexion by 24%, thus hindering the users' natural gait.

Contact Pressure

The mechanical forces exerted by the exoskeleton's structure result in pressure on the contact or interface area between the user and the exoskeleton. This pressure, known as contact stress, can be measured perpendicular to and parallel to the contact area. Forces acting perpendicularly or parallel to the contact area are normal and shear stresses, respectively (69).

Pressure is unavoidable when there is contact between the user and the exoskeleton's links and joints. It is important to minimize pressure to prevent potential negative effects such as bruises and blisters. Shear forces generated at the contact surface between the user's skin and the exoskeleton create friction. This friction leads to persistent, localized pressure on the skin and soft tissues, which can cause long-term health issues. The soft tissues surrounding the contact area cannot withstand high pressure (69). Prolonged intense pressure at the point of contact between the user's body and the exoskeleton can impede blood flow or compress tissue, resulting in bruising (81). Additionally, the strap used to secure the exoskeleton frame to the user's body may subject nearby soft tissues to shear stress. According to Gorgey (82), thigh straps create contact pressure ranging from 80-120mmHg, which may lead to skin and soft tissue injuries. Baunsgaard (83) used the Ekso Bionics exoskeleton to treat gait in patients with spinal cord injuries and observed that some patients developed pressure ulcers at the contact points with the exoskeleton. It has been shown that the mechanical force exerted on the user's body creates contact pressure, leading to discomfort and injuries in the skin and soft tissues, ultimately affecting user satisfaction and acceptance of the exoskeleton (84,85).

Postural Control

Postural control is related to human sensory and nervous systems that provide fundamental motor functions for maintaining body postures and stability to perform daily routine tasks (86). In any posture or activity, Pollock (87) defines control of posture as the human endeavour to maintain, achieve, or restore the body's centre of gravity or line of gravity within the base of support. One of the crucial factors that must be considered in the design of an exoskeleton is postural control. An exoskeleton user requires good postural control to maintain his/ her body in stable postures for standing, walking, or lifting objects while wearing the exoskeleton. A proper design of the exoskeleton's main structure and parts should not interfere with postural control to warrant the user's stability while working with the exoskeleton. Stability refers to the ability of the human body to return to its original position or regain balance after experiencing a disturbance. It encompasses the body's ability to maintain equilibrium and resist external forces that may disrupt its position. Achieving stability is crucial for performing tasks effectively and safely, particularly when interactions between humans and exoskeletons occur. When the line of gravity or the body's centerline is displaced from the base of support, postural control can sense the instability or unbalance of the body, and uses muscular activities to counteract the gravitational pull to prevent the body from falling (87).

In applying the exoskeleton for industrial tasks, postural control is perceived to be influenced primarily by the physical demands and user acceptance, especially for the work processes that require frequent movement or dynamic body postures. There are issues on exoskeleton design pertaining to postural control reported by previous studies. Alabdulkarim and Nussbaum (88) performed a simulated industrial drilling task as a case study. User feedback from the case study was that the entire body exoskeleton (FORTIS™ Exoskeleton) affected postural stability, making it difficult to control postural balance. High sitting on the lower-limb exoskeleton Chairless Chair led to discomfort and less balanced in terms of control of posture for clip fitting, screwing, and cable mounting chores (5). A study by Kim (89) observed an additional challenge for users to compromise postural control or body balance while wearing an upper extremity vest exoskeleton. Fig. 2 shows a user struggling to stabilize his posture while donning a lower limb exoskeleton.

Metabolic Cost

The overall energy used by the body to carry out physical actions like walking and industrial job processes is known as the metabolic cost. Expressions for metabolic cost include metabolic energy used up per unit of time, and metabolic energy used up per unit of distance (90). Activation and deactivation of skeletal muscles allow the movement of body parts for mobility, stability, and postural control. There is a substantial relationship between the metabolic cost and the (de)activation of muscles (91). It is well reported in the literature that exoskeletons help support physical demands to handle different task requirements (92–94). Furthermore, with the aid of the SPEXOR spinal exoskeleton, metabolic cost and muscle activation in repetitive lifting were reduced by 18% and 16%, respectively (95). A back-support exoskeleton minimized back muscle activation and metabolic cost of lifting tasks up to 57% and 18%, respectively (94). Another study demonstrated that an ankle exoskeleton could lower the metabolic and muscle activation costs of walking by 7.2% (96). A mechanical clutch exoskeleton reduces the metabolic expenditure of walking by 7.2–2.6%, according to a study by Collins (25). The lower-limb exoskeleton Chairless Chair helped lessen the muscle activation of the erector spinae in clip fitting, screwing, and cable mounting tasks (5).

Figure 2: A user has difficulty stabilizing his posture while donning a lower limb exoskeleton

However, improper exoskeleton design is potentially causing the users to activate greater muscle effort and higher energy consumption instead of minimizing the metabolic cost. When working with an exoskeleton, a user must apply muscle strength to wear the device and perform tasks. Parts of the processes include donning or doffing, lifting and carrying the device, manoeuvring the device and counteracting the gravitational force when the body is unbalanced. The heavier the exoskeletons, the more activation/ contraction of the muscles. A greater muscle contraction causes higher metabolic costs to be consumed. This has been evidenced by a previous study, in which wearing a trunk exoskeleton had increased metabolic costs by 17% during walking (97). Additionally, when muscles contract at their maximum continuously, they would fatigue more rapidly, leading to muscle strain.

Cognitive Workload

In the design and development of the exoskeletons, designers should not only emphasize the physical aspects (e.g. kinematic compatibility, contact pressure, etc.), but also consider the users' cognition characteristics. This means that the physical and cognitive elements should combine to satisfy the users' needs. Cognition is about the human's mental performance to acquire and process knowledge and information through sensing, perceiving, recognizing, memorizing, and thinking. Stirling (98) stressed that an exoskeleton system designed with cognitive fit can support human information processing, including somatosensation (e.g. sensory feedback related to pressure), executive function (e.g. working memory), and motor-action selection (e.g. activation of the muscles) when users are wearing the device.

Cognitive workload, or mental workload and mental demand, refers to the amount of working memory in the brain employed for processing information when the brain is thinking to accomplish a task (99). The cognitive workload of users working with the exoskeleton needs to be examined thoroughly so that the device would not affect mental performance. When users work with exoskeletons with light or low cognitive workload, then it is good for their mental health. Contrarily a high sustained cognitive workload can cause mental fatigue, frustration and stress. For example, the PAEXO (a passive upper limb exoskeleton) reduced the perceived workload of four industrial workers in an automotive assembly factory (100). However, the study by Zhu (101) observed that the existing exoskeleton designs accentuated physical fit but oversaw cognitive fit. In other words, the exoskeletons worn by industrial workers or patients may reduce the musculoskeletal loadings during task handling or exercises. However, at the same time, the device increases cognitive demands. As an illustration, a team of physiotherapists using the Ekso bionic exoskeleton for neurological rehabilitation claimed that using the equipment needed a high and consistent level of cognitive workload (102), which could lead to mental stress. Findings in (103) revealed that the visual reaction time of a group of users is slower when wearing a powered exoskeleton. The study suggested considering cognitive fit in the design and implementation of the said device. As a result, in order for the exoskeleton to be used effectively, the user's cognitive performance must be maintained appropriately (104). This paper summarized that the cognitive workload should be minimal to achieve user acceptance and wider applications.

Task Demands and Workplace Conditions

Exoskeletons have been recognized as a useful device to enhance the capability and endurance of users for industrial purposes, especially in handling heavy materials and repetitive tasks (72). The innovative design of the exoskeleton benefits many sectors, including construction or manufacturing industries, healthcare, rehabilitation and training (105,106), military tasks (71,107,108), and sports (109). Application of the exoskeleton in the construction or manufacturing industries can be seen in lifting tasks (110), screwing tasks (111), and bolting tasks (112). The healthcare sector includes patient handling tasks (54) and elderly care (113). Some exoskeletons are designed to be effective for specific types of task demands, such as lifting activities at industrial workplaces (93). In the manufacturing industry, since there are lots of tasks or work processes, there is no exoskeleton that is able to support all the tasks or work processes. This is why a specific design of exoskeleton for special task is needed (114).

Industrial tasks such as drilling and screwing have specific procedures or process flows and supporting equipment/ machines (e.g. portable grinders, powered screwdrivers and hand drills). The exoskeleton should not interfere with and affect the work performance of users (e.g. productivity and efficiency) in executing the tasks. The exoskeleton's action or mobility should precisely correspond to: the postures and movement of the user, the force needed to manipulate the task, the frequency or cycle of the tasks, size and speed of the supporting equipment/ machines. An exoskeleton that fits the user's body and does not impede the workflow during work will encourage the users to perceive the device with high acceptance and usability (115). However, exoskeletons are not a cure for all. Even though the exoskeletons proved helpful in lifting tasks, the devices tend to restrict the users from walking (80). In this regard, a study (115) revealed that two luggage handlers perceived the lifting task as easy to do when wearing exoskeletons. However, the other two handlers did not sense any advantages.

Furthermore, the safety aspect requires proper attention so that the exoskeleton will not cause workplace accidents (e.g. falling and entanglement). The exoskeleton should be quickly and safely detachable when users perform industrial jobs and encounter hazards like pinch, trip, and snag. Before purchasing exoskeletons, employers should pay attention and put efforts to check the devices suitability for harmonizing exoskeleton usage with secondary activities at the workplace, such as ascending or descending stairs, ramps, and ladders (116). In addition, the exoskeleton should allow the user to walk through narrow passages (e.g. between two machines) to avoid the potential risk of being stuck. Subsequently, the exoskeleton should not hinder the ability of users to operate materials-handling equipment such as trolleys and pallet trucks. In the case of an emergency (e.g. fire), exoskeleton users should still be able to open and close the emergency doors. Moreover, the exoskeletons can still permit the users to perform hand-operated tasks such as typing keyboards and operating machines or controlling the room's control panels. Last but not least, when wearing an exoskeleton, the user should be free from incompatibility with personal protective equipment, including safety gloves, safety boots, body harness, and safety jacket (117).

DISCUSSION

Current Trends of Ergonomic Exoskeletons

Exoskeleton is a wearable device that has close interaction with the users. Based on the review results, the authors have highlighted six ergonomics factors that need to be considered by designers and manufacturers when designing and developing exoskeletons that are not only compatible but also have harmonious interaction with the physical and cognitive of the users, task demands, and workplace conditions. The current trends for achieving harmonious interaction corresponding to each ergonomics factor are discussed in the following subsections.

Kinematic Compatibility

Based on the literature, 'Exoskeleton Harmony' is one of the exoskeletons with good kinematic compatibility (141). Previous studies have proposed the following methods and strategies to achieve kinematic compatibility of exoskeletons:

1. The number of degrees of freedom (DOF) of the exoskeleton and human body parts should presumably be near to equal (118).
2. To design the exoskeleton's joint with a self-aligning mechanism (79).
3. The links of the exoskeleton should allow extension and retraction to accommodate various heights of users (119).
4. Passive DOF with joint self-alignment (120).
5. Passive linear joints (121).
6. Bionic design and adjustable structure (122).
7. Adaptive admittance control law (123).
8. Use compatible elements, add kinematic redundancy, and do manual alignment (76).
9. Artificial tendons for actuating and restoring force to the fingers (124).

Contact Pressure

Sharp corners in the mechanical structure of the exoskeleton (even padded) can exert contact pressure on the users' skin and soft tissues while attaching the exoskeleton to the user's body. To ensure that the pressure is evenly distributed across a greater region, it is preferable to design the mechanical structure of the exoskeleton with rounded edges. Additionally, the following methods and strategies have been proposed by previous studies to circumvent excessive contact pressure:

1. Provides cushioning pad to the exoskeleton frame (125).
2. A sensory system to monitor the mechanical pressure on the users' skin (126).
3. Real-time strap pressure sensor to monitor contact pressure and provide feedback on the amount of pressure exerted by the user (127).

Postural Control

In this review, the authors recommend the following strategies in designing exoskeletons for good postural control and body balance:

1. When developing sit-stand exoskeletons, the line of gravity of the user's body falls within the base of support of the device;
2. Design a larger area of the support base of the exoskeleton. A foot module that increases the base of the support area is helpful in increasing postural stability when wearing a sit-stand exoskeleton (128).
3. A closer gap between the exoskeleton's support base and the user's centre of mass;
4. Previous studies applied McKibben pneumatic artificial muscles as an actuator for various exoskeleton applications such as:
   a. Glove exoskeleton for finger postural control (129,130).
   b. Upper limb exoskeleton to augment worker in overhead tasks (131).
   c. Elbow exoskeleton to assist users in elbow flexion/extension movement (132).

Metabolic Cost

A lightweight, compact structure and well-designed actuation system can contribute to minimal metabolic costs (133). Examples of light and simple exoskeletons include XoSoft lower-limb exoskeleton (134) and Achilles ankle exoskeleton. The following design strategies are useful for achieving lower metabolic costs:

1. A brushless direct current motor-powered leg exoskeleton reduced the metabolic cost of walking by 8% (135).
2. Integrated frame exoskeleton with actuator, Bowden cable, inertial measurement unit (IMU), and force sensor, decreased the metabolic expenditure of walking by 9.98% (136).
3. A hip exoskeleton improved walking's metabolic cost by 13.2% thanks to its lightweight mechanism, powerful motor, flexible frames, and adaptive control algorithm (137).
4. A soft pneumatic elbow exoskeleton reduced the metabolic cost by 32% in carrying load (138).
5. Bi-articular pneumatic artificial muscles with spring-powered knee, ankle, and foot exoskeletons lowered the metabolic expenditure of walking by 13% (139).

Cognitive Workload

Simple and minimal interface designs are preferred to realize the intuitive application of the exoskeleton. Additionally, the following strategies have proven helpful in minimizing the cognitive workload of users wearing and working with the exoskeleton:

1. Providing adequate training, time, and resources (e.g. user manual) (102).
2. Application of depth camera images for environment recognition and parameterization to control the lower-limb exoskeletons (140).
3. The use of brain/neural-computer interfaces for arm exoskeleton (141).
4. Group discussion among users for developing clear protocols for using the exoskeleton in neurological rehabilitation (102).
5. Hand exoskeleton with portable brain interface for hemiplegic patients to help them accomplish daily tasks (142).
6. Integrating a brain–machine interface system in the lower-limb exoskeleton for assisting people with tetraplegia (143).
7. Internet of Things (IoT) architecture with Natural User Interface based on gestures for rehabilitation programs of the elderly (144).
8. Considering ecological interface design to

display information about the complex constraints and relationships of the work environment in a style that makes it possible to directly and easily understand the information (145).

Task Demands and Workplace Conditions

Besides harmonious interaction with the users, the usage of exoskeletons should not be causing collisions in performing tasks or while operating machines or equipment in the work area. It is advisable to conduct direct observations and investigations of the tasks and work areas in which the exoskeletons will be applied so that their characteristics, demands and constraints can be considered in the design stage of the exoskeleton. The following methods and strategies are highly recommended to prevent collisions:

1. Focus group technique. Involvement of stakeholders such as primary users (e.g. industrial workers, patients, and health care professionals), secondary users (e.g. caregivers), technicians, and production engineers in the early stage of the design process of the exoskeleton. Through this technique, the designers of the exoskeleton would be able to determine the users' needs directly from the individuals who will be using or responsible for the device. The users' needs that can be obtained from the focus group include user comfort, individual adjustability, independence in taking it on and off, and gradual adjustment of support (146). Additionally, the outcomes of the focus group may reveal the relevant themes for the exoskeleton, such as characteristics of users, perceived advantages, cultural and environmental variables, and intervention factors (147).
2. Quality Function Deployment (QFD). The QFD is a design methodological tool requiring the designers to perform a survey of needs from the potential users, and benchmarking of available commercial exoskeletons. The outcome of QFD analysis enabled designers to determine design requirements, component characteristics, fabrication process requirements and production needs of the exoskeletons (148,149).
3. Provide adequate clearance between the exoskeleton and the machine/ work process. Adequate clearance prevents exoskeleton users from getting stuck, stumbled or entangled while moving around the workplace. This can be achieved by optimizing and deploying a proper arrangement of work station and the entire workplace layout. Recently, Dahmen (150) developed an objective method called as ExoScore & ExoMatch, and a Smart Adaptive Exoskeletons to match the exoskeletons and the workplace conditions.

Table II summarizes all the identified ergonomics factors about their roles and effects for achieving harmonious interaction between the user and task in exoskeleton applications.

Challenges of Ergonomic Exoskeletons

It is a great challenge for engineers or product designers to design an exoskeleton compatible with human kinematics. This is due to the complex flexibility of human body parts, such as the wrist and shoulder, particularly their degree of freedom (DOF). Exoskeleton designers must consider how their devices will be able to closely mimic the motions of various human body parts and achieve precise alignment between the exoskeleton and the user. According to Spositio (151), several factors

Table II: Summary of ergonomics factors determining working in harmony with exoskeletons

Ergonomics Factors	What Is It?	Why Is It Important?	How To Achieve?
Kinematic compatibility	A perfect alignment between the user's body parts and the mechanical structures of the exoskeleton to allow harmonious motion while using the device.	Kinematic incompatibility causes disrupted body motion, hindered natural gait, and discomfort. Thus, affecting user performance.	(1) Degree of freedom of the exoskeleton and human body parts should be equal. (2) Adjustability of the exoskeleton's parts to match user's body.
Contact pressure	Physical stress occurs at the contact area between the user and the exoskeleton.	Prolonged/ high pressure causes restricted blow flow or compressed tissue, which can lead to bruises.	(1) Provides cushioning pad to the exoskeleton frame. (2) Remove sharp corners on the exoskeleton.
Postural control	The motor functions to keep the user in a stable posture for standing, walking, or lifting objects while wearing the exoskeleton.	A poorly designed exoskeleton affects postural stability and difficult to control body balance. These may lead to discomfort and low user performance.	Shorter distance between the center of mass of the user and the base of the exoskeleton.
Metabolic cost	Amount of energy consumed by the user to perform tasks when wearing the exoskeleton.	Improper design of the exoskeleton can cause the users to activate greater muscle effort and consume extra energy. High probability for muscle fatigue and strain.	Should manufacture an exoskeleton with a lightweight, compact structure, and a well-designed actuation system.
Cognitive workload	Information processing of user such as somatosensation, working memory, and motor-action selection when users wearing the exoskeleton.	A persistent high cognitive workload can lead to mental fatigue, frustration and stress while working with the exoskeleton. These issues affect the user acceptance of the device.	(1) A simple/ minimal interface design for usability of the exoskeleton. (2) Provides training, time, and guide/ manual to users to ease adoption and familiarization of the exoskeleton.
Task demands and workplace conditions	Industrial tasks (e.g. drilling, screwing, and lifting objects). Rehabilitations/ exercises (e.g. gait training). Arrangement of workstation and entire workplace layout.	1) To ensure the exoskeleton does not interfere the task process flow 2) To prevent workplace accidents such as falling and entanglement.	Performs study on the tasks and the work areas so that their characteristics, demands and constraints will be considered in designing the exoskeleton. It should be easily detachable when the users are facing hazards such as snag while doing the tasks.

can cause kinematic incompatibility, including passive DOF, compliance in bracing, and ergonomics fitting problems with the exoskeletons (e.g., passive joints with a lacking ROM). Human factors engineering, particularly anthropometry or body dimension, is crucial for the exoskeleton to fit the user.

Furthermore, the mass and size of the exoskeleton need a thorough study during the design stage to aim for a low metabolic cost. A heavy and large exoskeleton structure is associated with demanding physical effort and consuming greater energy costs to work together. In addition, exoskeletons must be designed and used with care to account for the users' cognitive workload to prevent the devices from being overly taxing (104). A new user of an exoskeleton may struggle to wear and work with the device if the structural design, user interface, software applications (Apps), and operating procedures are too complex. As a result, user interface design greatly influences how users engage with exoskeletons.

Future Directions and Research Opportunities

Exoskeletons are developing as with many other technologies of assistive devices, thanks to the use of artificial intelligence (AI) methodologies, which will arguably have a greater impact on user experience. Almost all active exoskeletons on the market today can actuate joints and stimulate force to muscles; however, they lack the intelligence to function independently. Therefore, many technical improvements still need to be made to the control systems of the exoskeletons, particularly in the AI techniques such as kinematic/motion compatibility and cognitive workload, as some devices still fall short of these requirements.

In the control system of an exoskeleton, algorithms operate behind the interface of the device. One of the algorithms is artificial neural networks (ANN). The ANN, consisting of three layers (input, hidden, and output), is now extensively utilised to regulate kinematics. However, the lengthy execution times required to achieve smooth motion open new research directions. Deep learning techniques with more than three layers can also enhance motion performance. For the development of autonomous control systems for exoskeletons, integrating deep learning techniques and state-of-the-art sensors such as inertial measurement units is useful for identifying and assessing human activity and payload (152). The AI-based autonomous control systems may benefit the exoskeleton users when exploiting signals from muscle activity (electromyography, EMG) and neural activity from the brain (electroencephalography, or EEG). Thanks to the Internet of Things (IoT), the transmission and processing of EMG and EEG signals have become more efficient for generating appropriate instructions for the autonomous exoskeletons (153).

The success of the application and implementation of exoskeletons in the community and industry is highly dependent on the harmonious interaction between the users and the exoskeletons. The harmonious interaction is strongly influenced by physical ergonomics related to kinematic compatibility, contact pressure, postural control, and metabolic cost. In addition, cognitive ergonomics attributes such as aesthetics and perceived enjoyment when wearing and working with the exoskeleton are comparable in enhancing the user experience. It is necessary to conduct more research, especially on algorithm awareness (57) in order to develop personalised algorithms for autonomous exoskeletons that will improve the user experience. Algorithmic experience (AX) may improve the user's interaction with the personalised algorithms in adopting exoskeleton technology. In the context of algorithm ecology, AX can affect how users perceive algorithmic systems, providing helpful insights into creating human-centered algorithm systems (154). In addition, it will be helpful to have an assessment tool that assesses physical and cognitive ergonomics factors to produce exoskeletons that meet user experience requirements (73).

CONCLUSION

The authors have provided and discussed the ergonomics factors in this work, potentially enabling the users to work in harmony with the exoskeletons in different applications. The authors searched the published journal articles and conference proceedings from the Web of Science, Scopus, and Google Scholar databases by considering the publishing date from the year 2015 to the present. It was noted that applications of exoskeletons in many sectors, such as manufacturing and construction industries, healthcare and rehabilitation centers, and the military, have shown promising results in augmenting users' physical strength. The authors concluded that kinematic compatibility, contact pressure, postural control, metabolic cost, cognitive workload, as well as task demands and workplace conditions are the ergonomics factors determining working in harmony with the exoskeletons.

The synchronous operation of the mechanical components of the exoskeleton and the user's body parts is one of the fundamental prerequisites for kinematic compatibility. The mechanical force exerted on the user's body parts during exoskeleton use generates contact pressure. This contact pressure can have adverse effects, including discomfort and potential damage to the skin and soft tissues. These negative outcomes can result in reduced user satisfaction and may impact the user's acceptance of using the exoskeleton. An exoskeleton user needs adequate postural control to keep his or her body in stable positions whether standing, walking, or lifting objects while wearing the exoskeleton. In order to ensure the user's stability while using the exoskeleton, the main structure and components of the exoskeleton should be designed properly so as not to interfere with postural control. Exoskeletons can be useful in supporting physical demands, particularly when it comes to metabolic cost and muscle activation for manual material handling tasks. In order to prevent the exoskeleton from impairing mental function, users' cognitive workload while wearing the technology must be carefully assessed. Finally, there should be free from incompatibility issues between the user's exoskeleton and personal protection equipment, such as safety gloves, boots, body harnesses, and safety jackets.

This review acknowledges certain limitations. The authors only included journal articles published in the English language, which may have resulted in the exclusion of relevant information or studies published in other languages. As a result, there is a possibility that important findings or research might have been overlooked and not included in this review. It is important to consider this limitation and recognize the potential for additional insights from studies conducted in other languages.

ACKNOWLEDGEMENTS

This study was funded by the Ministry of Higher Education of Malaysia under grant number FRGS/1/2022/TK10/UTEM/02/4. A special thank you goes to the Faculty of Manufacturing Engineering and the Centre for Research and Innovation Management (CRIM) of Universiti Teknikal Malaysia Melaka.

REFERENCES

1. Lowe BD, Billotte WG, Peterson DR. ASTM F48 Formation and standards for industrial exoskeletons and exosuits. IISE Trans Occup Ergon Hum Factors [Internet]. 2019 Oct 2;7(3–4):230–6. doi:10.1080/24725838.2019.1579769
2. Ali A, Fontanari V, Schmoelz W, Agrawal SK. Systematic review of back-support exoskeletons and soft robotic suits. Frontiers in Bioengineering and Biotechnology . 2021; 9: 765257.doi: 10.3389/fbioe.2021.765257
3. Schwartz M, Theurel J, Desbrosses K. Effectiveness of soft versus rigid back-support exoskeletons during a lifting task. Int J Environ Res Public Health. 2021 Aug 1;18(15). doi: 10.3390/ijerph18158062.
4. Ippolito D, Constantinescu C, Riedel O. Holistic planning and optimization of human-centred workplaces with integrated Exoskeleton technology. Procedia CIRP. 2020 Jan 1;88:214–7. doi: 10.1016/j.procir.2020.05.038
5. Luger T, Seibt R, Cobb TJ, Rieger MA, Steinhilber B. Influence of a passive lower-limb exoskeleton during simulated industrial work tasks on physical load, upper body posture, postural control and discomfort. Appl Ergon. 2019 Oct 1;80:152–60. doi: 10.1016/j.apergo.2019.05.018
6. Pillai M v., van Engelhoven L, Kazerooni H. Evaluation of a lower leg support exoskeleton on floor and below hip height panel work. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2020 Mar 9 [cited 2022 Nov 10];62(3):489–500. doi:10.1177/0018720820907752
7. Hensel R, Keil M. Subjective Evaluation of a Passive industrial exoskeleton for lower-back support: A field study in the automotive sector. IISE Trans Occup Ergon Hum Factors [Internet]. 2019 Oct 2 [cited 2022 Nov 10];7(3–4):213–21. doi:10.1080/24725838.2019.1573770
8. Magdum RM, Jadhav SM. Design and implementation of chair less seating arrangement for industrial workers and farmers. GRD Journal for Engineering [Internet]. 2018;3. Available from: www.grdjournals.com
9. Ranaweera RKPS, Gopura RARC, Jayawardena TSS, Mann GKI. Development of a passively powered knee exoskeleton for squat lifting. Journal of Robotics, Networking and Artificial Life [Internet]. 2018;5(1):45–51. doi: 10.2991/jrnal.2018.5.1.11
10. Guncan B, Unal R. ANT-M: Design of passive lower-limb exoskeleton for weight-bearing assistance in industry. Biosystems and Biorobotics [Internet]. 2019 [cited 2022 Nov 10];22:500–4. doi:10.1007/978-3-030-01887-0_97
11. Li Z, Zhang T, Xue T, Du Z, Bai O. Effect evaluation of a wearable exoskeleton chair based on surface EMG. Chinese Control Conference, CCC. 2019 Jul 1;2019-July:4638–42. doi: 10.23919/ChiCC.2019.8865673
12. Zhu A, Shen Z, Shen H, Song J. Design and preliminary experimentation of passive weight-support exoskeleton. 2018 IEEE International Conference on Information and Automation, ICIA 2018. 2018 Aug 1;761–5. doi: 10.1109/ICInfA.2018.8812412
13. Zhu A, Shen Z, Shen H, Wu H, Zhang X. Design of a passive weight-support exoskeleton of human-machine multi-link. 2018 15th International Conference on Ubiquitous Robots, UR 2018. 2018 Aug 20;296–301. doi: 10.1109/URAI.2018.8441899
14. Raut V, Raut N. Fabrication of body's exoskeleton weight lifter and wearable chair. International Journal for Innovative Research in Science & Technology. 2018;5(1):139–45.
15. Akshay P, kshitij P, prafull N, ganesh pagar, V GT. Design of wearable chair. International Research Journal of Engineering and Technology [Internet]. 2018; Available from: https://www.irjet.net/archives/V5/i4/IRJET-V5I4169.pdf
16. Han B, Du Z, Huang T, Zhang T, Li Z, Bai O, et al. Mechanical framework design with experimental verification of a wearable exoskeleton chair. Proc IEEE Int Conf Robot Autom. 2019 May 1;2019-May:4040–5. doi: 10.1109/ICRA.2019.8794466
17. Delicia Elisheba D, Britto Y, Christina VPF.

Chair-less chair for lumbar pain reduction. International Journal of Mechanical Engineering and Technology9 (11). 2018;500–7.

18. Malode SM, Zilpe P, Ukani N, Chakhole S. Design of lower-limb exoskeletal. 2020 6th International Conference on Advanced Computing and Communication Systems, ICACCS 2020. 2020 Mar 1;682–6. doi: 10.1109/ICACCS48705.2020.9074211
19. Agarwal MS, Swanand K, Abhijit J, Mahesh K, Author C. Review on application of lower body exoskeleton. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN [Internet]. 2018 [cited 2022 Nov 10];2018. Available from: https://www.iosrjournals.org/iosr-jmce/papers/NCRIME-2018/Volume-2/6.%2031-33.pdf
20. Wijegunawardana ID, Kumara MBK, de Silva HHMJ, Viduranga PKP, Ranaweera RKPS, Gopura RARC, et al. ChairX: A robotic exoskeleton chair for industrial workers. IEEE International Conference on Rehabilitation Robotics. 2019 Jun 1;2019-June:587–92. doi: 10.1109/ICORR.2019.8779501
21. Chowdhury R, Poddar KK, Alam MA, Kumar S, Ahmed N, Som M. Design and implementation of portable healthcare chair (PHC) based on ergonomics. Proceedings of the 4th International Conference on Contemporary Computing and Informatics, IC3I 2019. 2019 Dec 1;154–9. doi: 10.1109/IC3I46837.2019.9055655
22. Collo A, Bonnet V, Venture G. A quasi-passive lower limb exoskeleton for partial body weight support. Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics. 2016 Jul 26;2016-July:643–8. doi: 10.1109/BIOROB.2016.7523698
23. Sasaki K, Sugimoto M, Sugiyama T, Paez Granados DF, Suzuki K. Child-sized passive exoskeleton for supporting voluntary sitting and standing motions. IEEE International Conference on Intelligent Robots and Systems. 2018 Dec 27;5457–62. doi: 10.1109/IROS.2018.8593744
24. Rajasekaran V, Vinagre M, Aranda J. Event-based control for sit-to-stand transition using a wearable exoskeleton. IEEE International Conference on Rehabilitation Robotics. 2017 Aug 11;400–5. doi: 10.1109/ICORR.2017.8009280
25. Collins SH, Bruce Wiggin M, Sawicki GS. Reducing the energy cost of human walking using an unpowered exoskeleton. Nature 2015 522:7555 [Internet]. 2015 Apr 1 [cited 2022 Nov 20];522(7555):212–5. doi: 10.1038/nature14288.
26. dos Santos WM, Nogueira SL, de Oliveira GC, Peca GG, Siqueira AAG. Design and evaluation of a modular lower limb exoskeleton for rehabilitation. IEEE International Conference on Rehabilitation Robotics. 2017 Aug 11;447–51. doi: 10.1109/ICORR.2017.8009288
27. Fernandes CR, Fernandes BL, Ranciaro M, Nohama P. Model proposal for development of a passive exoskeleton for lower limb medical devices view project Transcutaneous diaphragmatic synchronized pacing View project. Anais COBEC-SEB 2017 [Internet]. 2018 [cited 2022 Nov 10]; doi: 10.29327/cobecseb.78856
28. Hall ML, Lobo MA. Design and development of the first exoskeletal garment to enhance arm mobility for children with movement impairments. Assistive Technology [Internet]. 2017 Oct 20 [cited 2022 Nov 10];30(5):251–8. doi:10.1080/10400435.2017.1320690
29. Wang T, Zhang B, Liu C, Liu T, Han Y, Wang S, et al. A Review on the rehabilitation exoskeletons for the lower limbs of the elderly and the disabled. Electronics 2022, Vol 11, Page 388 [Internet]. 2022 Jan 27 [cited 2022 Nov 10];11(3):388. doi: 10.3390/electronics11030388
30. Galle S, Derave W, Bossuyt F, Calders P, Malcolm P, de Clercq D. Exoskeleton plantarflexion assistance for elderly. Gait Posture. 2017 Feb 1;52:183–8. doi: 10.1016/j.gaitpost.2016.11.040.
31. Walsh CJ, Endo K, Herr H. A quasi-passive leg exoskeleton for load-carrying augmentation. International Journal of Humanoid Robotics. 2011 Nov 20;4(3):487–506. doi: 10.1142/S0219843607001126
32. Mudie K, Billing D, Bishop DJ, Vee P, Lee S. Reducing load carriage during walking using a lower limb passive exoskeleton. International Society of Biomechanics [Internet]. 2017 [cited 2022 Nov 19]; Available from: https://www.researchgate.net/publication/319057276
33. Chaichaowarat R, Kinugawa J, Kosuge K. Unpowered knee exoskeleton reduces quadriceps activity during cycling. Engineering. 2018 Aug 1;4(4):471–8. doi: 10.1016/j.eng.2018.07.011
34. Hasegawa Y, Ogura K. First report on passive exoskeleton for easy running: PEXER IV. 2013 International Symposium on Micro-NanoMechatronics and Human Science, MHS 2013. doi: 10.1109/MHS.2013.6710481
35. Koopman AS, NΔf M, Baltrusch SJ, Kingma I, Rodriguez-Guerrero C, Babič J, et al. Biomechanical evaluation of a new passive back support exoskeleton. J Biomech. 2020 May 22;105:109795. doi: 10.1016/j.jbiomech.2020.109795
36. Koopman AS, Kingma I, de Looze MP, van Dieën JH. Effects of a passive back exoskeleton on the mechanical loading of the low-back during symmetric lifting. J Biomech. 2020 Mar 26;102:109486. doi: 10.1016/j.jbiomech.2019.109486
37. Koopman AS, Toxiri S, Power V, Kingma I, van Dieën JH, Ortiz J, et al. The effect of control strategies for an active back-support exoskeleton on spine loading and kinematics during lifting. J Biomech. 2019 Jun 25;91:14–22. doi: 10.1016/j.jbiomech.2019.04.044
38. de Vries AW, Krause F, de Looze MP. The effectivity

of a passive arm support exoskeleton in reducing muscle activation and perceived exertion during plastering activities. Ergonomics [Internet]. 2021 [cited 2022 Nov 19];64(6):712–21.doi:10.1080/00140139.2020.1868581

39. Luger T, BΔr M, Seibt R, Rimmele P, Rieger MA, Steinhilber B. A passive back exoskeleton supporting symmetric and asymmetric lifting in stoop and squat posture reduces trunk and hip extensor muscle activity and adjusts body posture – A laboratory study. Appl Ergon. 2021 Nov 1;97:103530. doi: 10.1016/j.apergo.2021.103530
40. Kuber PM, Rashedi E. Product ergonomics in industrial exoskeletons: potential enhancements for workforce efficiency and safety. Theoretical Issues in Ergonomic Science [Internet]. 2020 [cited 2022 Nov 19];22(6):729–52. doi:10.1080/1463922X.2020.1850905
41. Kim J, Kim J, Jung Y, Lee D, Bae J. A passive upper limb exoskeleton with tilted and offset shoulder joints for assisting overhead tasks. IEEE/ASME Transactions on Mechatronics. 2022. doi: 10.1109/TMECH.2022.3169617
42. Brahmi B, Saad M, Lam JTAT, Luna CO, Archambault PS, Rahman MH. Adaptive control of a 7-DOF exoskeleton robot with uncertainties on kinematics and dynamics. Eur J Control. 2018 Jul 1;42:77–87. doi: 10.1016/j.ejcon.2018.03.002
43. ISO. ISO 9241-210: 2019 Ergonomics of humansystem interaction-Part 210: Human-centred design for interactive systems. Switzerland Geneva; 2019.
44. Weckenborg C, Thies C, Spengler TS. Harmonizing ergonomics and economics of assembly lines using collaborative robots and exoskeletons. J Manuf Syst. 2022 Jan 1;62:681–702. doi: 10.1016/j.jmsy.2022.02.005
45. Ciccarelli M, Papetti A, Cappelletti F, Brunzini A, Germani M. Combining World Class Manufacturing system and Industry 4.0 technologies to design ergonomic manufacturing equipment. International Journal on Interactive Design and Manufacturing [Internet]. 2022 Mar 1 [cited 2022 Nov 19];16(1):263–79. doi:10.1007/s12008-021-00832-7
46. Keebler JR, Rosen MA, Sittig DF, Thomas E, Salas E. Human factors and ergonomics in healthcare: Industry demands and a path forward. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2022 Jan 8 [cited 2022 Nov 19];64(1):250–8. doi:10.1177/00187208211073623
47. Bairwa RC, Meena ML, Dangayach GS, Jain R. Prevalence of musculoskeletal disorders among the agricultural workers: A review. Lecture Notes in Networks and Systems [Internet]. 2022 [cited 2022 Nov 19];391:439–46. doi:10.1007/978-3-030-94277-9_38
48. Howard J, Murashov VV, Lowe BD & Lu L. Industrial Exoskeletons: Need for Intervention Effectiveness Research. American Journal of Industrial Medicine, 2020; 63(3):201-208, doi:10.1002/ajim.23080. Accessed 1 Nov. 2023.
49. Kalita B, Narayan J, Dwivedy SK. Development of active lower limb robotic-based orthosis and exoskeleton devices: A systematic review. Int J Soc Robot [Internet]. 2021 Jul 1 [cited 2022 Nov 19];13(4):775–93. doi:10.1007/s12369-020-00662-9
50. Kapsalyamov A, Jamwal PK, Hussain S, Ghayesh MH. State of the art lower limb robotic exoskeletons for elderly assistance. IEEE Access. 2019;7:95075–86. doi: 10.1109/ACCESS.2019.2928010
51. Shore L, Power V, de Eyto A, O'Sullivan LW. Technology acceptance and user-centred design of assistive exoskeletons for older adults: A commentary. Robotics 2018, Vol 7, Page 3 [Internet]. 2018 Jan 3 [cited 2022 Nov 19];7(1):3. doi: 10.3390/robotics7010003
52. Kumar K, Shanmugam D, Min SN, Subramaniyam M. Assistive technologies for biologically inspired controller system - a short review assistive technologies for the elderly. Proceedings of the 3rd International Conference on Inventive Systems and Control, ICISC 2019. 2019 Jan 1;292–6. doi: 10.1109/ICISC44355.2019.9036407
53. Chen B, Zi B, Qin L, Pan Q. State-of-the-art research in robotic hip exoskeletons: A general review. J Orthop Translat. 2020 Jan 1;20:4–13. doi: 10.1016/j.jot.2019.09.006.
54. Zheng L, Hawke AL, Evans K. Critical review on applications and roles of exoskeletons in patient handling. Int J Ind Ergon. 2022 May 1;89:103290. doi: 10.1016/j.ergon.2022.103290
55. Pinto-Fernandez D, Torricelli D, Sanchez-Villamanan MDC, Aller F, Mombaur K, Conti R, et al. Performance evaluation of lower limb exoskeletons: a systematic review. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2020 Jul 1;28(7):1573–83. doi: 10.1109/TNSRE.2020.2989481
56. Zhou J, Yang S, Xue Q. Lower limb rehabilitation exoskeleton robot: A review. Advances in Mechanical Engineering [Internet]. 2021 Apr 22 [cited 2022 Nov 19];13(4):1–17. doi:10.1177/16878140211011862
57. Shin D, Kee KF, Shin EY. Algorithm awareness: Why user awareness is critical for personal privacy in the adoption of algorithmic platforms? Int J Inf Manage. 2022 Aug 1;65. doi: 10.1016/j.ijinfomgt.2022.102494
58. Meng Q, Zeng Q, Xie Q, Fei C, Kong B, Lu X, et al. Flexible lower limb exoskeleton systems: A review. NeuroRehabilitation. 2022 Jan 1;50(4):367–90. doi: 10.3233/NRE-210300.
59. du Plessis T, Djouani K, Oosthuizen C. A Review of active hand exoskeletons for rehabilitation and assistance. Robotics 2021, Vol 10, Page

40 [Internet]. 2021 Mar 3 [cited 2022 Nov 19];10(1):40. doi: 10.3390/robotics10010040

60. Sun Y, Tang Y, Zheng J, Dong D, Chen X, Bai L. From sensing to control of lower limb exoskeleton: a systematic review. Annu Rev Control. 2022 Jan 1;53:83–96. doi: 10.1016/j.arcontrol.2022.04.003
61. Alqahtani MS, Cooper G, Diver C, B6rtolo PJ. Exoskeletons for Lower Limb Applications: A Review. Bio-Materials and Prototyping Applications in Medicine [Internet]. 2021 [cited 2022 Nov 20];139–64. doi:10.1007/978-3-030-35876-1_8
62. Halder S, Kumar A. An overview of artificial intelligence-based soft upper limb exoskeleton for rehabilitation: a descriptive review. 2023. doi: 10.48550/arXiv.2301.04336
63. Bogue R. Exoskeletons: a review of recent progress. Industrial Robot. 2022 Jun 30;49(5):813–8. doi: 10.1108/IR-04-2022-0105
64. Vélez-guerrero MA, Callejas-cuervo M, Mazzoleni S. Artificial intelligence-based wearable robotic exoskeletons for upper limb rehabilitation: A review. Sensors (Basel). 2021;21(6):2146. doi: 10.3390/s21062146.
65. Wu Z, Yang M, Xia Y, Wang L. Mechanical structural design and actuation technologies of powered knee exoskeletons: a review. Vol. 13, Applied Sciences (Switzerland). MDPI; 2023. doi: 10.3390/app13021064
66. Martínez-Mata A, Blanco-Ortega A, Guzmán-Valdivia C, Abúndez-Pliego A, García-Velarde M, Magadán-Salazar A, et al. Engineering design strategies for force augmentation exoskeletons: A general review. Int J Adv Robot Syst [Internet]. 2023 Jan 1 [cited 2023 Feb 10];20(1):172988062211494. doi: 10.1177/17298806221149473
67. Masengo G, Zhang X, Dong R, Alhassan AB, Hamza K, Mudaheranwa E. Lower limb exoskeleton robot and its cooperative control: A review, trends, and challenges for future research. Neurorobot. 2023; doi: 10.3389/fnbot.2022.913748
68. Farzaneh M, Farzaneh MM. A review study on the design of an exoskeleton robot. International Journal of Scientific and Technical Research in Engineering (IJSTRE) www.ijstre.com [Internet]. 2021 [cited 2022 Nov 20];6(3). Available from: www.ijstre.com
69. Armitage L, Turner S, Sreenivasa M. Human-device interface pressure measurement in prosthetic, orthotic and exoskeleton applications: A systematic review. Med Eng Phys. 2021 Nov 1;97:56–69. doi: 10.1016/j.medengphy.2021.09.008
70. Sanchez-Villamacan MDC, Gonzalez-Vargas J, Torricelli D, Moreno JC, Pons JL. Compliant lower limb exoskeletons: a comprehensive review on mechanical design principles. Journal of NeuroEngineering and Rehabilitation 2019 16:1 [Internet]. 2019 May 9 [cited 2022 Nov 20];16(1):1–16. doi:10.1186/s12984-019-0517-9
71. Proud JK, Lai DTH, Mudie KL, Carstairs GL, Billing DC, Garofolini A, et al. Exoskeleton application to military manual handling tasks. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2020 Nov 18 [cited 2022 Nov 20];64(3):527–54. doi:10.1177/0018720820957467
72. Zhu Z, Dutta A, Dai F. Exoskeletons for manual material handling – A review and implication for construction applications. Autom Constr. 2021 Feb 1;122:103493. doi: 10.1016/j.autcon.2020.103493
73. Massardi S, Rodriguez-Cianca D, Pinto-Fernandez D, Moreno JC, Lancini M, Torricelli D. Characterization and Evaluation of Human–Exoskeleton Interaction Dynamics: A Review. Sensors (Basel). 2022;22(11):3993. doi: 10.3390/s22113993.
74. Halim I, Saptari A, Abdullah Z, Perumal PA, Zaimi M, Abidin Z, et al. Critical factors influencing user experience on passive exoskeleton application: A review. International Journal of Integrated Engineering [Internet]. 2022 Jun 21 [cited 2022 Nov 20];14(4):89–115. doi: 10.30880/ijie.2022.14.04.009
75. Basenach L, Renneberg B, Salbach H, Dreier M, Wulfling K. Systematic reviews and meta-analyses of treatment interventions for Internet use disorders: Critical analysis of the methodical quality according to the PRISMA guidelines. J Behav Addict. 2023; 12(1):9-25. doi: 10.1556/2006.2022.00087.
76. Naf MB, Junius K, Rossini M, Rodriguez-Guerrero C, Vanderborght B, Lefeber D. Misalignment compensation for full human-exoskeleton kinematic compatibility: state of the art and evaluation. Appl Mech Rev [Internet]. 2018 Sep 1 [cited 2022 Nov 20];70(5). doi: 10.1115/1.4042523
77. de la Tejera JA, Bustamante-Bello R, Ramirez-Mendoza RA, Izquierdo-Reyes J. Systematic review of exoskeletons towards a general categorization model proposal. Applied Sciences 2021, Vol 11, Page 76 [Internet]. 2020 Dec 24 [cited 2022 Nov 20];11(1):76. doi: 10.3390/app11010076
78. Ishmael MK, Archangeli D, Lenzi T. A powered hip exoskeleton with high torque density for walking, running, and stair ascent. IEEE/ASME Transactions on Mechatronics. 2022; doi: 10.1109/TMECH.2022.3159506
79. Sarkisian S v., Ishmael MK, Lenzi T. Self-aligning mechanism improves comfort and performance with a powered knee exoskeleton. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2021;29:629–40. doi: 10.1109/TNSRE.2021.3064463
80. Poliero T, Sposito M, Toxiri S, Natali C di, Iurato M, Sanguineti V, et al. Versatile and non-versatile occupational back-support exoskeletons: A comparison in laboratory and field studies. Wearable Technologies [Internet]. 2021 [cited 2022 Nov 20];2:e12. doi: 10.1017/wtc.2021.9

81. Bessler J, Prange-Lasonder GB, Schaake L, Saenz JF, Bidard C, Fassi I, et al. Safety assessment of rehabilitation robots: A review identifying safety skills and current knowledge gaps. Front Robot AI. 2021 Mar 22;8:33. doi: 10.3389/frobt.2021.602878
82. Gorgey AS. Robotic exoskeletons: The current pros and cons. World J Orthop [Internet]. 2018 Sep 9 [cited 2022 Nov 20];9(9):112. doi: 10.5312/wjo.v9.i9.112.
83. Bach Baunsgaard C, Vig Nissen U, Katrin Brust A, Frotzler A, Ribeill C, Kalke YB, et al. Gait training after spinal cord injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics. Spinal Cord 2017 56:2 [Internet]. 2017 Nov 6 [cited 2022 Nov 20];56(2):106–16. doi: 10.1038/s41393-017-0013-7.
84. Qu X, Qu C, Ma T, Yin P, Zhao N, Xia Y, et al. Effects of an industrial passive assistive exoskeleton on muscle activity, oxygen consumption and subjective responses during lifting tasks. PLoS One [Internet]. 2021 Jan 1 [cited 2022 Nov 20];16(1):e0245629. doi:10.1371/journal.pone.0245629
85. Huysamen K, de Looze M, Bosch T, Ortiz J, Toxiri S, O'Sullivan LW. Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. Appl Ergon. 2018 Apr 1;68:125–31. doi: 10.1016/j.apergo.2017.11.004
86. Hyon SH, Morimoto J, Matsubara T, Noda T, Kawato M. XoR: Hybrid drive exoskeleton robot that can balance. 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2011 Dec 6;3975–81. doi: 10.1109/IROS.2011.6048840
87. Pollock AS, Durward BR, Rowe PJ, Paul JP. What is balance? Clin Rehabil [Internet]. 2016 Jul 1 [cited 2022 Nov 20];14(4):402–6. doi:10.1191/0269215500cr342oa
88. Alabdulkarim S, Nussbaum MA. Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task. Appl Ergon. 2019 Jan 1;74:55–66. doi: 10.1016/j.apergo.2018.08.004
89. Kim S, Nussbaum MA, Mokhlespour Esfahani MI, Alemi MM, Jia B, Rashedi E. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II – "Unexpected" effects on shoulder motion, balance, and spine loading. Appl Ergon. 2018 Jul 1;70:323–30. doi: 10.1016/j.apergo.2018.02.024.
90. Faraji S, Wu AR, Ijspeert AJ. A simple model of mechanical effects to estimate metabolic cost of human walking. Scientific Reports 2018 8:1 [Internet]. 2018 Jul 20 [cited 2022 Nov 20];8(1):1–12. doi: 10.1038/s41598-018-29429-z.
91. Lemaire KK, Jaspers RT, Kistemaker DA, Soest AJK van, Laarse WJV der. Metabolic cost of activation and mechanical efficiency of mouse soleus muscle fiber bundles during repetitive concentric and eccentric contractions. Front Physiol. 2019;10(JUN):760. doi: 10.3389/fphys.2019.00760
92. Hwang J, Kumar Yerriboina VN, Ari H, Kim JH. Effects of passive back-support exoskeletons on physical demands and usability during patient transfer tasks. Appl Ergon. 2021 May 1;93:103373. doi: 10.1016/j.apergo.2021.103373
93. Nussbaum MA, Lowe BD, Looze M de, Harris-Adamson C, Smets M. An Introduction to the Special Issue on Occupational Exoskeletons. IISE Trans Occup Ergon Hum Factors [Internet]. 2020 Oct 2 [cited 2022 Nov 20];7(3–4):153–62. doi:10.1080/24725838.2019.1709695
94. Kim S, Madinei S, Alemi MM, Srinivasan D, Nussbaum MA. Assessing the potential for "undesired" effects of passive back-support exoskeleton use during a simulated manual assembly task: Muscle activity, posture, balance, discomfort, and usability. Appl Ergon. 2020 Nov 1;89:103194. doi: 10.1016/j.apergo.2020.103194.
95. Baltrusch SJ, van Dieën JH, Koopman AS, Näf MB, Rodriguez-Guerrero C, Babič J, et al. SPEXOR passive spinal exoskeleton decreases metabolic cost during symmetric repetitive lifting. European Journal of Applied Physiology 2019 120:2 [Internet]. 2019 Dec 11 [cited 2022 Nov 20];120(2):401–12. doi:10.1007/s00421-019-04284-6
96. Zhou T, Xiong C, Zhang J, Hu D, Chen W, Huang X. Reducing the metabolic energy of walking and running using an unpowered hip exoskeleton. J Neuroeng Rehabil [Internet]. 2021 Dec 1 [cited 2022 Nov 20];18(1):1–15. doi:10.1186/s12984-021-00893-5
97. Baltrusch SJ, van Dieʌn JH, Bruijn SM, Koopman AS, van Bennekom CAM, Houdijk H. The effect of a passive trunk exoskeleton on functional performance and metabolic costs. Biosystems and Biorobotics [Internet]. 2019 [cited 2022 Nov 20];22:229–33. doi:10.1007/978-3-030-01887-0_44
98. Stirling L, Kelty-Stephen D, Fineman R, Jones MLH, Daniel Park BK, Reed MP, et al. Static, dynamic, and cognitive fit of exosystems for the human operator. Hum Factors [Internet]. 2020 May 1 [cited 2022 Nov 20];62(3):424–40. doi:10.1177/0018720819896898
99. Naismith LM, Cheung JJH, Sibbald M, Tavares W, Cavalcanti RB, Haji FA, et al. Using cognitive load theory to optimize simulation design. Clinical Simulation: Education, Operations and Engineering. 2019 Jan 1;129–41. doi: 10.1016/B978-0-12-815657-5.00010-3
100. Maurice P, Čamernik J, Gorjan D, Bornmann J, Tagliapietra L, Latella C, et al. Evaluation of PAEXO, a novel passive exoskeleton for overhead work. Comput Methods Biomech Biomed Engin [Internet]. 2020 May 1 [cited 2022 Nov 20];22(sup1):S448–50.

doi: 10.1080/10255842.2020.1714977

101. Zhu Y, Weston EB, Mehta RK, Marras WS. Neural and biomechanical tradeoffs associated with human-exoskeleton interactions. Appl Ergon. 2021 Oct 1;96:103494. doi: 10.1016/j.apergo.2021.103494
102. Read E, Woolsey C, McGibbon CA, O'Connell C. Physiotherapists' experiences using the ekso bionic exoskeleton with patients in a neurological rehabilitation hospital: A qualitative study. Rehabil Res Pract. 2020;2020. doi: 10.1155/2020/2939573
103. Bequette B, Norton A, Jones E, Stirling L. Physical and cognitive load effects due to a powered lower-body exoskeleton. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2020 Mar 23 [cited 2022 Nov 20];62(3):411–23. doi:10.1177/0018720820907450
104. la Bara LMA, Meloni L, Giusino D, Pietrantoni L. Assessment methods of usability and cognitive workload of rehabilitative exoskeletons: a systematic review. Applied Sciences 2021, Vol 11, Page 7146 [Internet]. 2021 Aug 2 [cited 2022 Nov 20];11(15):7146. doi: 10.3390/app11157146
105. Dragusanu M, Iqbal MZ, Baldi TL, Prattichizzo D, Malvezzi M. Design, development, and control of a hand/wrist exoskeleton for rehabilitation and training. IEEE Transactions on Robotics. 2022 Jun 1;38(3):1472–88. doi: 10.1109/TRO.2022.3172510
106. Gao M, Wang Z, Pang Z, Sun J, Li J, Li S, et al. Electrically driven lower limb exoskeleton rehabilitation robot based on anthropomorphic design. Machines 2022, Vol 10, Page 266 [Internet]. 2022 Apr 7 [cited 2022 Nov 20];10(4):266. doi: 10.3390/machines10040266
107. Farris DJ, Harris DJ, Rice HM, Campbell J, Weare A, Risius D, et al. A systematic literature review of evidence for the use of assistive exoskeletons in defence and security use cases. Ergonomics [Internet]. 2022 [cited 2022 Nov 20]; doi:10.1080/00140139.2022.2059106
108. Leova L, Cubanova S, Kutilek P, Volf P, Hejda J, Hybl J, et al. Current state and design recommendations of exoskeletons of lower limbs in military applications. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) [Internet]. 2022 [cited 2022 Nov 20];13207 LNCS:452–63. doi:10.1007/978-3-030-98260-7_29
109. Miller DE, Tan GR, Farina EM, Sheets-Singer AL, Collins SH. Characterizing the relationship between peak assistance torque and metabolic cost reduction during running with ankle exoskeletons. J Neuroeng Rehabil [Internet]. 2022 Dec 1 [cited 2022 Nov 20];19(1):1–15. doi:10.1186/s12984-022-01023-5
110. Park H, Kim S, Nussbaum MA, Srinivasan D. Effects of using a whole-body powered exoskeleton during simulated occupational load-handling tasks: A pilot study. Appl Ergon. 2022 Jan 1;98:103589. doi: 10.1016/j.apergo.2021.103589
111. Pinho JP, Forner-Cordero A. Shoulder muscle activity and perceived comfort of industry workers using a commercial upper limb exoskeleton for simulated tasks. Appl Ergon. 2022 May 1;101:103718. doi: 10.1016/j.apergo.2022.103718.
112. McFarland TC, McDonald AC, Whittaker RL, Callaghan JP, Dickerson CR. Level of exoskeleton support influences shoulder elevation, external rotation and forearm pronation during simulated work tasks in females. Appl Ergon. 2022 Jan 1;98:103591. doi: 10.1016/j.apergo.2021.103591
113. Sposito M, Poliero T, di Natali C, Semprini M, Barresi G, Laffranchi M, et al. Exoskeletons in elderly healthcare. Studies in Computational Intelligence [Internet]. 2022 [cited 2022 Nov 20];1011:353–74. doi:10.1007/978-981-16-8488-3_17
114. Dahmen C, Hulzel C, Wullecke F, Constantinescu C. Approach of optimized planning process for exoskeleton centered workplace design. Procedia CIRP. 2018 Jan 1;72:1277–82. doi: 10.1016/j.procir.2018.03.185
115. Baltrusch SJ, Houdijk H, van Dieʌn JH, Kruif JTCM de. Passive trunk exoskeleton acceptability and effects on self-efficacy in employees with low-back pain: a mixed method approach. J Occup Rehabil [Internet]. 2021 Mar 1 [cited 2022 Nov 20];31(1):129–41. doi:10.1007/s10926-020-09891-1
116. Joudzadeh P, Hadi A, Tarvirdizadeh B, Borooghani D, Alipour K. Design and fabrication of a lower limb exoskeleton to assist in stair ascending. Industrial Robot. 2019 May 7;46(2):290–9. doi: 10.1108/IR-09-2018-0199
117. Ralfs L, Hoffmann N, Weidner R. Method and test course for the evaluation of industrial exoskeletons. Applied Sciences 2021, Vol 11, Page 9614 [Internet]. 2021 Oct 15 [cited 2022 Nov 20];11(20):9614. doi: 10.3390/app11209614
118. Li Z, Ren Z, Zhao K, Deng C, Feng Y. Human-cooperative control design of a walking exoskeleton for body weight support. IEEE Trans Industr Inform. 2020 May 1;16(5):2985–96. doi: 10.1109/TII.2019.2900121
119. Christensen S, Rafique S, Bai S. Design of a powered full-body exoskeleton for physical assistance of elderly people. Int J Adv Robot Syst [Internet]. 2021 Nov 10 [cited 2022 Nov 20];18(6). doi:10.1177/17298814211053534
120. Cempini M, Cortese M, Vitiello N. A powered finger-thumb wearable hand exoskeleton with self-aligning joint axes. IEEE/ASME Transactions on Mechatronics. 2015 Apr 1;20(2):705–16. doi: 10.1109/TMECH.2014.2315528
121. Chishty HA, Zonnino A, Farrens AJ, Sergi F. Kinematic compatibility of a wrist robot with cable

differential actuation: effects of misalignment compensation via passive joints. IEEE Trans Med Robot Bionics. 2021 Nov 1;3(4):970–9. doi: 10.1109/TMRB.2021.3123528

122. Liu J, Li H, Chen W, Wang J. A novel design of pressure sensing foot for lower limb exoskeleton. Proceedings of the 2013 IEEE 8th Conference on Industrial Electronics and Applications, ICIEA 2013. 2013;1517–20. doi: 10.1109/ICIEA.2013.6566608
123. Lian P, He Y, Ma Y, Liu J, Wu X. Adaptive admittance control of human-exoskeleton system using RNN optimization. 2021 IEEE International Conference on Real-Time Computing and Robotics, RCAR 2021. 2021 Jul 15;584–9. doi: 10.1109/RCAR52367.2021.9517398
124. Rudd G, Daly L, Jovanovic V, Cuckov F. A Low-cost soft robotic hand exoskeleton for use in therapy of limited hand–motor function. Applied Sciences 2019, Vol 9, Page 3751 [Internet]. 2019 Sep 8 [cited 2022 Nov 20];9(18):3751. doi: 10.3390/app9183751
125. Wu Q, Wang X, Du F, Zhang X. Design and control of a powered hip exoskeleton for walking assistance. Int J Adv Robot Syst [Internet]. 2015 Mar 10 [cited 2022 Nov 20];12. doi:10.5772/59757
126. Marquardt C, Weiner P, Dezman M, Asfour T. Embedded barometric pressure sensor unit for force myography in exoskeletons. In: IEEE-RAS International Conference on Humanoid Robots. IEEE Computer Society; 2022. p. 67–73. doi: 10.1109/Humanoids53995.2022.10000204
127. Tamez-Duque J, Cobian-Ugalde R, Kilicarslan A, Venkatakrishnan A, Soto R, Contreras-Vidal JL. Real-time strap pressure sensor system for powered exoskeletons. Sensors 2015, Vol 15, Pages 4550-4563 [Internet]. 2015 Feb 16 [cited 2022 Nov 20];15(2):4550–63. doi: 10.3390/s150204550.
128. Steinhilber B, Seibt R, Rieger MA, Luger T. Postural control when using an industrial lower limb exoskeleton: impact of reaching for a working tool and external perturbation. Hum Factors. 2022;64(4):635-648. doi: 10.1177/0018720820957466
129. Takahashi N, Takahashi H, Koike H. Soft exoskeleton glove enabling force feedback for human-like finger posture control with 20 degrees of freedom. 2019 IEEE World Haptics Conference, WHC 2019. 2019 Jul 1;217–22. doi: 10.1109/WHC.2019.8816142
130. Takahashi N, Furuya S, Koike H. Soft Exoskeleton Glove with Human Anatomical Architecture: Production of Dexterous Finger Movements and Skillful Piano Performance. IEEE Trans Haptics. 2020 Oct 1;13(4):679–90. doi: 10.1109/TOH.2020.2993445
131. Paterna M, Magnetti Gisolo S, de Benedictis C, Muscolo GG, Ferraresi C. A passive upper-limb exoskeleton for industrial application based on pneumatic artificial muscles. Mechanical Sciences. 2022 Apr 27;13(1):387–98. doi: 10.5194/ms-13-387-2022
132. Zhao Z, Hao L, Liu M, Gao H, Li X. Prescribed performance model-free adaptive terminal sliding mode control for the pneumatic artificial muscles elbow exoskeleton. Journal of Mechanical Science and Technology 2021 35:7 [Internet]. 2021 Jun 29 [cited 2022 Nov 20];35(7):3183–97. doi:10.1007/s12206-021-0639-4
133. Junius K, Lefeber N, Swinnen E, Vanderborght B, Lefeber D. Metabolic effects induced by a kinematically compatible hip exoskeleton during STS. IEEE Trans Biomed Eng. 2018 Jun 1;65(6):1399–409. doi: 10.1109/TBME.2017.2754922
134. Ortiz J, Rocon E, Power V, de Eyto A, O'Sullivan L, Wirz M, et al. XoSoft - A vision for a soft modular lower limb exoskeleton. Biosystems and Biorobotics [Internet]. 2017 [cited 2022 Nov 20];16:83–8. doi:10.1007/978-3-319-46532-6_14
135. Mooney LM, Rouse EJ, Herr HM. Autonomous exoskeleton reduces metabolic cost of human walking during load carriage. J Neuroeng Rehabil [Internet]. 2014 May 9 [cited 2022 Nov 20];11(1):1–11. doi:10.1186/1743-0003-11-80
136. Leng Y, Huang G, Ma L, Qian Y, Chen X, Zhang K, et al. A Lightweight, Integrated and Portable Force-Controlled Ankle Exoskeleton for Daily Walking Assistance. 2021 27th International Conference on Mechatronics and Machine Vision in Practice, M2VIP 2021. 2021;42–7. doi: 10.1109/M2VIP49856.2021.9665002
137. Seo K, Lee J, Lee Y, Ha T, Shim Y. Fully autonomous hip exoskeleton saves metabolic cost of walking. Proc IEEE Int Conf Robot Autom. 2016 Jun 8;2016-June:4628–35. doi: 10.1109/ICRA.2016.7487663
138. Nassour J, Zhao G, Grimmer M. Soft pneumatic elbow exoskeleton reduces the muscle activity, metabolic cost and fatigue during holding and carrying of loads. Scientific Reports 2021 11:1 [Internet]. 2021 Jun 15 [cited 2022 Nov 20];11(1):1–14. doi: doi: 10.1038/s41598-021-91702-5.
139. Malcolm P, Galle S, Derave W, de Clercq D. Bi-articular knee-ankle-foot exoskeleton produces higher metabolic cost reduction than weight-matched mono-articular exoskeleton. Front Neurosci. 2018 Mar 2;12(MAR):69. doi: 10.3389/fnins.2018.00069
140. Karacan K, Meyer JT, Bozma HI, Gassert R, Samur E. An environment recognition and parameterization system for shared-control of a powered lower-limb exoskeleton. Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics. 2020 Nov 1;2020-November:623–8. doi: 10.1109/BioRob49111.2020.9224407
141. Badesa FJ, Diez JA, Catalan JM, Trigili E, Cordella F, Nann M, et al. Physiological responses during hybrid BNCI control of an upper-limb exoskeleton.

Sensors 2019, Vol 19, Page 4931 [Internet]. 2019 Nov 12 [cited 2022 Nov 20];19(22):4931. doi: 10.3390/s19224931

142. Asgher U, Khan MJ, Asif Nizami MH, Khalil K, Ahmad R, Ayaz Y, et al. Motor training using mental workload (MWL) with an assistive soft exoskeleton system: A Functional Near-Infrared Spectroscopy (fNIRS) Study for Brain–Machine Interface (BMI). Front Neurorobot. 2021 Mar 18;15:17. doi: 10.3389/fnbot.2021.605751.
143. Lee K, Liu D, Perroud L, Chavarriaga R, Millán J del R. A brain-controlled exoskeleton with cascaded event-related desynchronization classifiers. Rob Auton Syst. 2017 Apr 1;90:15–23. doi:10.1016/j.robot.2016.10.005
144. Pavyn-Pulido N, Lypez-Riquelme JA, Feliъ-Batlle JJ. IoT Architecture for smart control of an exoskeleton robot in rehabilitation by using a natural user interface based on gestures. Journal of Medical Systems 2020 44:9 [Internet]. 2020 Jul 23 [cited 2022 Nov 20];44(9):1–10. doi:10.1007/s10916-020-01602-w
145. Schewe F, Vollrath M. Ecological interface design effectively reduces cognitive workload – The example of HMIs for speed control. Transp Res Part F Traffic Psychol Behav. 2020 Jul 1;72:155–70. doi: 10.1016/j.trf.2020.05.009
146. Baltrusch SJ, Houdijk H, van Dieлn JH, van Bennekom CAM, de Kruif AJTCM. Perspectives of end users on the potential use of trunk exoskeletons for people with low-back pain: a focus group study. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2020 Jan 8 [cited 2022 Nov 20];62(3):365–76. doi:10.1177/0018720819885788
147. Cha JS, Monfared S, Stefanidis D, Nussbaum MA, Yu D. Supporting surgical teams: identifying needs and barriers for exoskeleton implementation in the operating room. Human Factors: The Journal of the Human Factors and Ergonomics Society [Internet]. 2019 Oct 8 [cited 2022 Nov 20];62(3):377–90. doi:10.1177/0018720819879271
148. Abdullah Z, Halim I, Maidin S, Md Ghazaly M, Amran Mohd Ali M., et al. Design and development of a flexible wearable sit-stand passive exoskeleton using quality function deployment. Proceedings of Mechanical Engineering Research Day 2020;308–9. Available from: https://www3.utem.edu.my/care/proceedings/merd20/pdf/08_Mechanical_Design_and_Optimization/133-p308_309.pdf
149. Aibin Z, Shengli H, Ziyue L, Yangyang L. Lower limb rehabilitation robot design with dual customized design: Customized gait and customized exoskeleton. 2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence, URAI 2016. 2016 Oct 21;572–5. doi: 10.1109/URAI.2016.7625782
150. Dahmen C, Constantinescu C. Methodology of employing exoskeleton technology in manufacturing by considering time-related and ergonomics influences. Applied Sciences 2020, Vol 10, Page 1591 [Internet]. 2020 Feb 27 [cited 2022 Nov 20];10(5):1591. doi: 10.3390/app10051591
151. Sposito M, Natali C di, Toxiri S, Caldwell DG, Momi E de, Ortiz J. Exoskeleton kinematic design robustness: An assessment method to account for human variability. Wearable Technologies [Internet]. 2020 [cited 2022 Nov 20];1:e7. doi: 10.1017/wtc.2020.7
152. Pesenti M, Invernizzi G, Mazzella J, Bocciolone M, Pedrocchi A, Gandolla M. IMU-based human activity recognition and payload classification for low-back exoskeletons. Sci Rep. 2023 Dec 1;13(1). doi; doi: 10.1038/s41598-023-28195-x.
153. Jacob S, Alagirisamy M, Xi C, Balasubramanian V, Srinivasan R, R. P, et al. AI and IoT-Enabled smart exoskeleton system for rehabilitation of paralyzed people in connected communities. IEEE Access. 2021;9:80340–50. doi: 10.1109/ACCESS.2021.3083093
154. Shin D, Zhong B, Biocca FA. Beyond user experience: What constitutes algorithmic experiences? Int J Inf Manage. 2020 Jun 1;52. doi:10.1016/j.ijinfomgt.2019.102061