IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 30 July 2023, accepted 5 September 2023, date of publication 11 October 2023, date of current version 24 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3323249

TOPICAL REVIEW

Exoskeletons for Manual Handling: A Scoping Review

S. PERERA, (Member, IEEE), K. N. D. WIDANAGE, (Graduate Student Member, IEEE), I. D. WIJEGUNAWARDANA, R. K. P. S. RANAWEERA, (Member, IEEE), AND R. A. R. C. GOPURA, (Member, IEEE)
Bionics Laboratory, Department of Mechanical Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka
Corresponding author: R. K. P. S. Ranaweera (pubudur@uom.lk)

ABSTRACT The prevalence of work-related musculoskeletal disorders is a common issue in many occupations involving manual handling activities. In order to aid manual workers in reducing the burden on the musculoskeletal system, various wearable robotic technologies have been developed over the years. An increase in research work on wearable technologies has been observed, particularly in the last decade. In that context, this article presents a comprehensive review and a bibliometric analysis of the recorded occupational exoskeletons for manual handling since 2010. The review is aimed at identifying the paradigm shifts of research in the recent past and associating the trends pertaining to the applications, mechanisms, and control systems in the development of wearable devices for manual handling. The scope of the review limits itself to active and passive exoskeletons designed to support the upper extremity, lower extremity, and spine for performing load lifting, load carrying, or static holding. The analysis of the results revealed the emerging trends with the aim of providing researchers with areas for improvement and suggestions for different clusters of devices.

INDEX TERMS Design and control, human-centered and life-like robotics, human performance augmentation, mechanics.

I. INTRODUCTION

According to World Health Organization (WHO), musculoskeletal disorders (MSDs) relate to the health issues in locomotor elements such as the skeleton, muscles, tendons, cartilage, nerves, and ligaments [1]. Although there are several risk factors contributing to these conditions, it has been clear from early research that the work-related component plays an important role in the incidence of MSDs. Many researchers agree that heavy workload and high repetitiveness of work in industrial settings cause or intensify the symptoms of MSDs; thus such MSDs are termed "work-related musculoskeletal disorders" (WMSDs) [2]. Although some of these conditions come from preventable causes, such as erroneous postures and ergonomically incorrect working conditions, some causes, such as repetitive exposure to heavy load manipulations, are not preventable with no external aid.

The associate editor coordinating the review of this manuscript and approving it for publication was Okyay Kaynak.

The most commonly occurring MSD of load manipulations is low back pain [1], of which 47.5% has resulted from environmental/occupational factors according to 2017 statistics of Global Burden of Health [3]. This highlights the requirement of prevention methods for WMSDs related to load manipulation.

WMSDs are not limited to industrial environments. In fact, the causal link between WMSDs related to load manipulation and occupations such as military and healthcare personnel (nurses, caregivers, etc.) has been a topic of discussion for a few decades. The technological advancement in modern warfare has resulted in heavier backpacks for soldiers, demanding load-carrying capacities of around 200 kg, thus increasing the risks of MSDs [4]. In healthcare services, the incidence of MSDs in nurses is over 40%, particularly resulting from lifting and moving patients [5]. As such, 'load handling' plays an important role in WMSDs.

Since load manipulation in an occupational context has proved to be a leading risk factor for WMSDs [6], and such WMSDs result in a higher economic burden in terms of treating the conditions, employee compensations, lost employee hours, and lost productivity of the work [7], researches had looked into external aids that can be used to prevent heavy physiological and psychological implications. It was required for such aids to not hinder any regular movements of the workers as well. As a solution, wearable devices that can augment human capabilities thus reducing the burden on the muscles were introduced.

One of the earliest recorded attempts at designing wearable devices or exoskeletons for power augmentation was in the 19th century, when a design of a passive device to augment walking, running, and jumping was patented despite having no record of the device implementation [8]. 70 years later, the issues in designing a power augmenting device for load-carrying applications were analyzed and a technical report was published with a proposal for the device by a researcher from the US Army Exterior Ballistics Laboratory. Unfortunately, this proposal was unsuccessful in securing funding, thus halting the project [13].

Officially, the first steps towards developing externally powered exoskeletons for power augmentation were taken by General Electric Company, through the 'Hardiman' project sponsored by the Office of Naval Research and US Army in the late 1960's [14]. Based on a control system with kinesthetic force feedback, this device was designed as a full-body exoskeleton for lifting and handling heavy loads up to 680 kg, with a strength enhancing factor of 25:1. Albeit the pioneering work, the 'Hardiman' project never moved past the prototype stage owing to several factors such as its high weight, unstable control, and funding restrictions [15]. Contemporarily, the research done in former Yugoslavia on powered assistive exoskeletons for people with physical challenges came into the spotlight with the development of the first powered assistive exoskeleton, 'Kinematic Walker' and later, 'Active Suit' [9], [16]. This shifted the focus of the field towards assistive robotics for physically challenged people, delaying the research output on power augmentation exoskeletons until the mid-1980s. Meanwhile, based on the work of 'Hardiman' project and another concept called 'Pitman' [17], a concept paper describing a powered full-body exoskeleton, 'Man-Amplifier', was published in the USA [8], [18].

At this time, Kazerooni re-initiated research on power-augmenting exoskeletons for handling heavy loads. This research led to one of the first research publications on powered upper limb exoskeletons for enhancing the power exerted by the wearer [11]. Known as the 'Extenders', these exoskeletons were based on the transfer of power and the information signals between the wearer and the device, so that the person can manipulate heavy objects while getting feedback on the magnitude of the force exerted [10]. This was the first step in a series of research conducted by the University of California, Berkley, on the development of Berkley Lower Extremity Exoskeleton, 'BLEEX' [19].

'BLEEX' was claimed to be the first "load-bearing and energetically autonomous" exoskeleton, and was designed with seven degrees of freedom (DOF), three at the hip and ankle separately, and one at the knee. With the ability to carry loads up to 34 kg, this device was specifically designed to keep the agility of the wearer intact and unrestricted [11]. 'BLEEX' was funded by the program, Exoskeletons for Human Performance Augmentation (EHPA) by the U.S. Defense Advanced Research Projects Agency (DARPA) initiated in 2001 [20]. DARPA also sponsored two other contemporary projects, 'Sarcos Exoskeleton' and 'MIT Exoskeleton', the first being a full-body 'Wearable Energetically Autonomous Robot (WEAR)' which can lift up to 84 kg [8] and the latter being a quasi-passive lower-limb exoskeleton for load-carrying augmentation which can transfer about 80% of the load to the ground with a payload of 36 kg [21].

Meanwhile, Japanese research on the topic was also advancing. The first commercially available exoskeleton, 'HAL-5', was introduced in 2005. This resulted from 10 years' worth of effort on the project, 'Hybrid Assistive Limb (HAL)', which was initially designed to assist people with degenerated muscles [20]. However, the commercial product was advertised as a multipurpose device which can be used for medical applications, heavy work support, rescue support, and entertainment [12]. It is also noteworthy to include research done by the Kanagawa Institute of Technology for introducing exoskeletons in different application area. Their device, 'Power Assist Suit', was designed to assist nurses and caregivers when handling and supporting patients, to avoid back injuries [22]. They claimed that this device can support a patient of 85 kg, without enforcing a burden on the wearer [20].

The important milestones of the exoskeletons through time are shown in Fig. 1. Inspired by many early designs discussed above, the research on power-augmenting exoskeletons has progressed more with the improvements to the complementing technologies. In the literature, numerous reviews assessing those devices can be identified since 2005 [23], [24], [25], [26].

A surge of interest in the development of manual handling exoskeletons can be seen in the last decade [27]. More recent reviews of manual handling exoskeletons have shown a focused approach, where the scope has been restricted by either the type of exoskeleton, location of support, or the application domain. Numerous reviews on lower-extremity exoskeletons have been published during the last decade focusing on different aspects such as design, control, actuation, and performance validation methodologies [28], [29], [30], [31]. Similarly, upper-extremity and back support exoskeletons have also been reviewed separately in different review articles [32], [33], [34], [35], [36]. A few reviews focusing on individual joints can also be found in the literature [37], [38]. When considering the application-focused approaches, the reviews on industrial exoskeletons

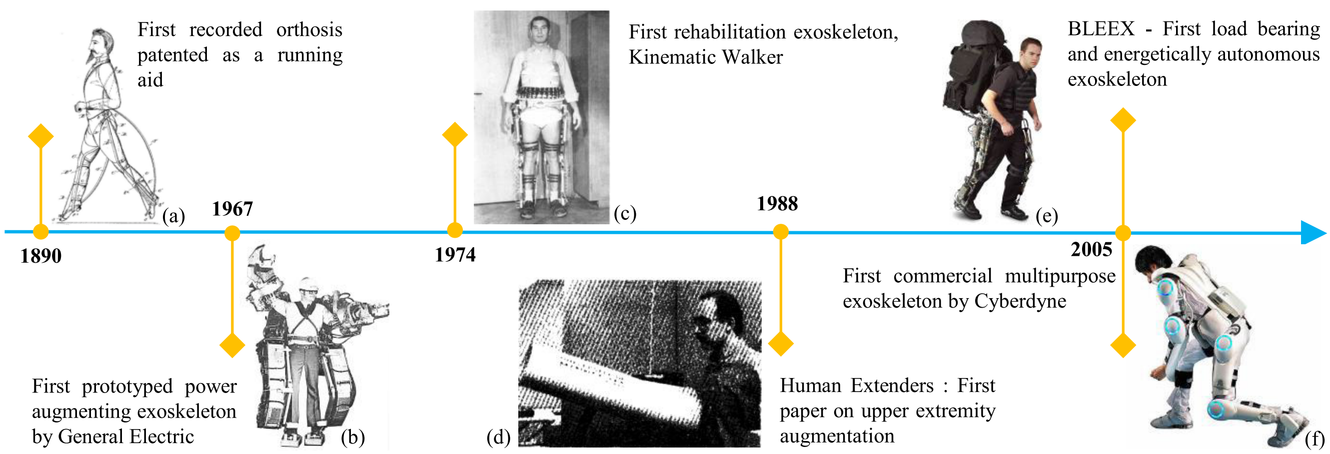

FIGURE 1. Important milestones in the research of exoskeletons: (a) First recorded orthosis [8], (b) First prototyped power augmenting exoskeleton [8], (c) First rehabilitation exoskeleton [9], (d) Human Extender [10], (e) First load bearing and energetically autonomous exoskeleton [11] (f) First commercial multipurpose exoskeleton [12].

and military exoskeletons take a prominent place in the literature [27], [39], [40], [41].

However, analyzing manual handling exoskeletons in separate domains can limit the ability to obtain an overall view of the research field. The different domains might have novel technologies and methodologies that are valid and relevant for other domains as well. Therefore, to provide a complete image of the field of manual handling exoskeletons, a more holistic approach is required.

Furthermore, a very limited number of bibliometric analyses have been performed on occupational exoskeletons. These analyses have limited scope such as either focused on a specific body part [42], or only on robotic exoskeletons [43]. A large number of research works on manual handling exoskeletons have been published in the last decade. A bibliometric analysis is required to analyze the trends in the shift of research focus of such a large volume of data [44]. However, according to the literature survey, the authors have not identified any bibliometric analysis that has been carried out on the manual handling exoskeletons collectively.

Identifying these requirements, in this article, the authors have analyzed the design and control of manual handling exoskeletons in a broader scope, focusing on both the review and the bibliometric analysis aspects.

This paper is structured as follows. In the next section, an overview of manual handling is presented which includes anatomy and biomechanics behind load lifting, carrying, and holding along with the related standards for manual handling. This is followed by methodology for literature search and classification of literature. Then the resulting review is presented in the following section which discusses the selected exoskeletons in the aspects of the application, the body part of interest, mechanical design, powering mechanisms, and control. Next, bibliometric analysis is presented from the screened literature. The final section presents the challenges, trends, and future directions for manual handling exoskeletons.

II. MANUAL HANDLING: ANATOMY, BIOMECHANICS, AND STANDARDS

Since the focus of wearable devices for power augmentation is to reduce the burden on humans while exerting high forces and torques, it is crucial to understand how the forces and torques are generated by the muscles. Therefore, studying the biomechanics of load handling is a very important step in developing such devices. However, before discussing the biomechanics of movements, one should familiarise with the commonly used terminology in the field.

Anatomical or cardinal planes are a set of hypothetical planes used to divide the body in three dimensions to describe the location and the direction of its movements. These planes are named as frontal plane (also known as the coronal plane), sagittal plane and transverse plane. The frontal plane, which is also known as the coronal plane, separates the body vertically into anterior (front) and posterior (back) halves. The sagittal plane splits the body vertically into left and right halves. The transverse plane divides the body into superior (top) and inferior (bottom) halves [45]. The graphical representation of the cardinal planes on three-dimensional space is given in Fig.2(a).

Pertaining to the joint movements and their axes, three basic pairs of terms are defined. Those terms are abduction/adduction (AB/AD), flexion/extension (FL/EX) and internal/external rotation (IR/ER). The joint movements happening in the frontal plane except for the case of the wrist joint are known as AB and AD where AB is the motion of the limb segments away from the midline of the body, while AD is the motion towards. The similar kinds of motions occurring in the wrist joint when a person is in the anatomical position are termed ulnar deviation and radial deviation respectively [33]. FL and EX are the terms that are used to

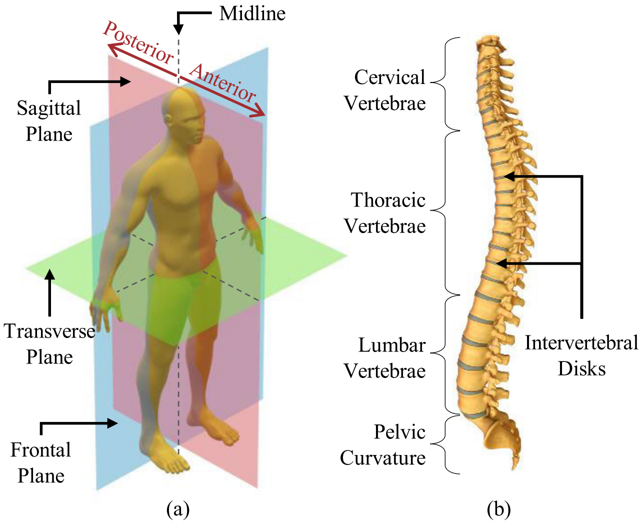

FIGURE 2. **(a) Anatomical reference planes of human body, (b) left lateral view of major regions of the spine.**

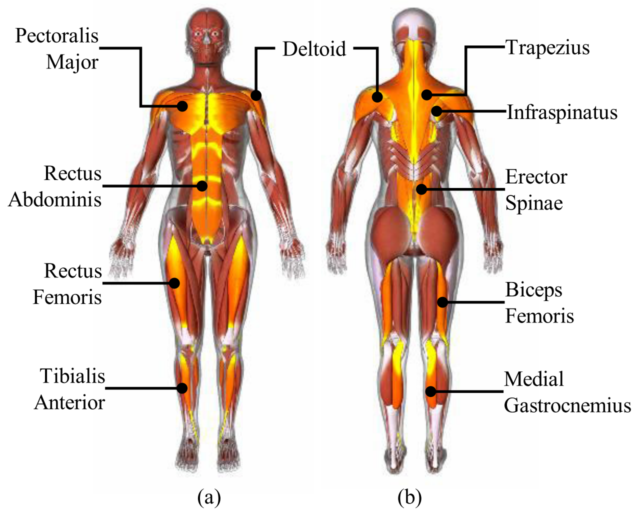

FIGURE 3. **Highly activated muscles during lifting task: (a) front view, (b) back view.**

identify the movements happening in the sagittal plane with the exception of the foot motion. FL is the movement of a body segment moving away from its natural anatomical position, and the opposite is referred to as EX. There is an additional term called hyperextension which describes the motion of the limb segment in the opposite direction of the FL. Foot motion in the sagittal plane deviates from this terminology by identifying the motion along the sagittal plane which moves the toe upwards as dorsiflexion and the motion in the opposite direction as plantarflexion. The limb movements occurring in the transverse plane (around the longitudinal axis) are termed IR or medial rotations when the limb movements happen towards the midline of the body and ER or lateral rotations when the rotation of the limb is away from the midline of the body. However, due to the complexity of some joints, their motions are not restricted to one of the cardinal planes. For example, the joints such as the talocrural joint of the ankle generate motions around an axis diagonal to the cardinal planes, thus making different motions than those described above. However, for ease of reference, the motions of the foot at the frontal plane are termed as inversion/eversion (IN/EV) and the motions parallel to the transverse plane are termed as IR/ER [45].

In load-handling activities, three body regions are mainly involved. Those regions are upper extremity, lower extremity and spine. In the upper extremity, the shoulder joint has mainly three DOFs over the three cardinal planes, and the elbow complex which includes the elbow joint and radioulnar joints has two DOFs. The wrist joint has two key DOFs, FL/EX and ulnar/radial deviation (UD/RD) [33]. In the lower extremity, the hip joint supports three DOFs over the cardinal planes and the knee joint has one DOF, FL/EX. Ankle also supports three DOFs over the three cardinal planes whose motions are described above. The spine consists of 33 vertebrae categorized into five regions out of which cervical, thoracic and lumbar regions are responsible for movements in the spine. Those regions are represented in Fig.2(b). Two adjacent vertebrae and the intervertebral disk between them are defined as a motion segment which is considered to possess six DOF due to the translational and rotational motions about the three cardinal planes. Although the motion generated in one motion segment is considerably small, the collective motion of a number of segments is responsible for various spinal movements. As a whole, the spine can generate rotational movements in all three cardinal planes and thus has three DOFs [45].

Since this review focuses on load-handling wearable devices, it is important to discuss the biomechanics involved in load lifting, load carrying, and static holding of loads.

A. LOAD LIFTING

Load lifting is one of the most frequently used manual material handling activities. There are three main techniques that are commonly used in load lifting; squat lifting, stoop lifting and semi-squat lifting [46]. These three techniques are described in terms of biomechanics of the spine and knee while lifting a load which is placed at the ground level. Squat lifting involves higher knee FL (up to 117°) [47] and erect spine posture. This is the most advised technique for load lifting due to the lower burden on the postural muscles of the spine. However, due to the high energy cost and rapid fatigue development in squat lifting compared to the stoop lifting technique, the latter is also used in load lifting [48]. In the stoop lifting technique, the knee is kept at a nearly extended position while the trunk undergoes high FL (about 90°) [46]. Semi-squat lifting is a combination of both techniques where both knee and spine are moderately flexed when starting the lifting operation.

Rectus abdominis and lumbar erector spinae are the trunk muscles that are activated when lifting a load from the ground level, irrespective of the technique. Activation of the lower extremity muscles varies depending on the lifting technique. Biceps femoris and rectus femoris show higher variances of activation during squat lifting, while tibialis anterior, medial gastrocnemius, and biceps femoris are activated with high variances in stoop lifting [49]. There are numerous upper extremity muscles that are activated during a load-lifting task. However, the muscles which show more than 50% of maximum voluntary contractions (MVC) are upper trapezius, infraspinatus, anterior deltoid, medial deltoid, middle trapezius superior and pectoralis major superior in the descending order of MVC. Biceps brachii, the muscle which is majorly responsible for elbow flexion, only shows a muscle activation of 30-50% of MVC, highlighting that the shoulder plays a more important role in the load-lifting tasks than the elbow [50]. The muscles which have a higher activation during the lifting task are shown in Fig. 3.

Since lower back pain is a commonly occurring condition of WMSDs, and the highest loading on the spine occurs due to handling of external loads such as lifting and carrying objects, it is important to investigate spinal loading during lifting tasks [47]. In general, several factors affect the loading conditions of the spine.

- The position of the object relative to the center of motion in the spine
- Initial and ending heights of the object
- The size, shape, weight, and density of the object
- The rate of loading
- The degree of flexion or rotation of the spine

Various studies have been carried out to investigate the limitations of static loading on the spine. The maximum compression forces that the vertebral column can withstand without failure, ranges from 5,000 N to 8,000 N. A bending moment of 620 Nm and a shear moment of 156 Nm has been identified as the maximum static moments before failure by one study. The same study has revealed that the maximum spine FL before failure is 20° with 9 mm horizontal displacement between two vertebrae. However, these values are highly dependent on the person's age, bone strength and the degree of disc degeneration [47].

Although a significant difference has not been revealed in shear and compression forces on the spine generated by stoop and squat lifting techniques, the likelihood of loss of balance in squat lifting is prominent, thus may incur additional stresses on the spine. However, stoop lifting shows a significant increase in intradiscal pressure, when compared with squat lifting [47].

B. STATIC HOLDING

Skeletal muscles have the ability to perform both dynamic and static work. Dynamic work is achieved when the muscle undergoes isokinetic contraction in which the muscle activation changes the muscle length, thus generating a motion such as lifting, ultimately performing mechanical work. In the case of static work, the muscle undergoes isometric contraction in which the muscle length is kept constant while applying a force without generating a motion [47]. Isometric contractions are responsible for maintaining the posture of the body. Therefore, in static holding of loads, the muscles undergo isometric contractions to hold the load in place.

The biomechanics behind the static holding of loads significantly depend on numerous factors which have been investigated through a number of studies [51], [52], [53], [54], [55]. These factors can be listed as human-related factors (age, gender, strength and endurance capacity), object-related factors (shape, size and weight of the object) and task-related factors (posture, holding height, offset from the body, duration, frequency, method of holding and symmetricity of load position).

Both upper body and lower body postures play an important role in the biomechanics of static holding. It has been realized that the lower body posture has a significant effect on the stability of the load-holding task [54]. A study performed on the endurance time while holding a load in different postures revealed that muscle fatigue is quicker when holding a load below the hip level with the knee flexed such as squatting, when compared with holding the load above the hip level such as standing [55]. The muscle activities in the trunk muscles are observed to be higher in the knee-flexed postures [53]. However, when handling the loads below the hip level with standing postures (knee-straight/trunk-bent), the endurance time improves with lower holding heights [55].

Many studies about static holding of loads focus on the muscle activities of upper limb and trunk muscles. Out of the trunk muscles, the muscle activities of latissimus dorsi, external obliques, rectus abdominis and erector spinae are commonly investigated while biceps brachii and brachioradialis are studied for the muscle activities in the upper limb [51], [52], [53].

C. LOAD CARRYING

Load carrying can be considered as a combination of static holding and walking. Therefore, while upper body muscles undergo isometric contractions, the lower body muscles must undergo isokinetic contractions to achieve the walking movement. Load-carrying tasks can be categorized into two modes as anterior load carriage and posterior load carriage, depending on whether the load is positioned in front of the body or behind the body, i.e., anteriorly or posteriorly. Anterior load carriage involves holding the load by hands, while posterior load carriage involves carrying the external load in a backpack-like arrangement.

In anterior load carriage, the biomechanics of the upper body remain similar to that of static holding. However, the posterior load carriage shows deviations from this. It has been revealed that energy efficiency when carrying the loads on the back of the torso is higher than carrying the loads in hands [56]. A significant leaning of the trunk is also observable with posterior load carriage since it moves the load center-of-mass closer to the line of action of the ground reaction force at the foot [56].

Load carriage also imposes changes on the gait biomechanics in the lower body. Maintaining stability is a key aspect of loaded gait, which is fulfilled by increasing the time duration in which the body is supported by both legs (double support) and by maintaining short, faster steps during walking [56], [57]. Studies done on joint moments reveal that the sensitivity of the knee joint to external loads is higher than other lower extremity joints. In loaded conditions, the stresses on the knee joint could rise as twice as that of the unloaded condition, depending on the magnitude of the load. The most prominent interaction of the knee joint under loads can be identified during the earlier stage of the stance phase, while the contribution of hip and ankle muscles is prominent in the push-off phase of the gait [56].

D. STANDARDS

ISO11228 presents an ergonomic approach to reduce or eliminate the risk of manual handling injuries from lifting, lowering, and carrying loads [58]. It specifies the recommended limits during manual handling and provides a systematic method for risk assessment. The four stages of risk assessment include peril recognition, hazard identification, risk estimation, and risk evaluation. Here, a step model is used to determine whether the conditions of lifting and/or carrying are acceptable.

In step 1, a procedure to estimate the recommended limit for the mass or load handled by the worker is presented. The reference mass for lifting has been specified based on the different populations. In the case of occupational/professional use, for lowering the risk of injury of up to 95% of the working population (male and female), the maximum limit for object mass is 23 kg.

In order to screen for repetitive tasks under step 2, the object mass needs to be determined in combination with lifting frequency. Here, the recommended limit for lifting frequency under ideal conditions is determined based on the object mass and of the total duration of lifts per day. As an example, for short-duration work (where the total duration of lifts does not exceed one hour per day), when lifting objects weighing up to 7 kg, the maximum recommended lifting frequency is 15 lifts/minute.

Step 3 should be used for the repetitive lifting tasks that include non-ideal working postures and object positioning. The recommended lifting limits for object mass are derived from an empirical model based on several assumptions, such as two-handed smooth lifting with the firm support of feet on the ground, the width of object 0.75 m or less, good coupling/gripping with unrestricted lifting posture, favourable environmental conditions. The equation for determining the limit for the object mass (m) is given below.

$$m \leq m_{ref} \times h_M \times v_M \times d_M \times \alpha_M \times f_M \times c_M \tag{1}$$

where m_{ref} is the reference mass for the population group, h_M is the horizontal distance multiplier, v_M is the vertical location multiplier, d_M is the vertical-displacement multiplier, α_M is the asymmetry multiplier, f_M is frequency multiplier, and c_M is coupling multiplier. The multipliers were estimated by considering the biomechanical, psychophysical, and physiological criteria. Interested readers may refer to standard documentation for additional information [59].

Step 4 describes the approach for screening the recommended limit for cumulative mass per day. The cumulative mass handled can be calculated as a product of object mass and frequency of lifting/ carrying. Since maximum reference mass and task frequency are 25 kg and 15 lifts/minute respectively, the recommended limit for cumulative mass is 10,000 kg per eight-hour duration of a day. However, for longer carrying distances (> 20 m) the limit should be reduced to 6,000 kg.

TABLE 1. Search terms used for literature search.

Action	Device	Outcome	Location
lift*	exoskeleton	augment*	pelvis
squat*	*suit	assist*	limb
stoop*	weara*	support*	*body
carry*	ortho*	transfer*	*arm
handl*	robot*	reduce	shoulder
hold*	garment	aid	back
bear*	device	enhanc*	spine*
bend*			spinal
walk*			torso
locomot*			lumbar
carriage			hip*
			trunk
			waist
			knee
			extremity
			muscle

Note: *Represents the wildcard symbol for end/beginning truncation of search terms during literature search.

III. REVIEW METHOD

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used as the basis for the study [60], [61]. Initially, several articles related to wearable devices for load handling were screened from preliminary literature searches in the SCOPUS database and from Google Scholar. Following the preliminary searches, the title and abstract were examined to identify search terms for the literature search. A list of search terms was compiled using several iterations of the above method. Identified search terms and their synonyms were grouped into four clusters of action of the device (Action), the possible name for the device (Device), end result of using the device (Outcome) and the location of the human body which is supported by the device (Location) as presented in Table 1.

A. ELIGIBILITY CRITERIA, INFORMATION SOURCES AND LITERATURE SEARCH

Using the search terms, following search query was obtained in conjunction with boolean operators and search locations in between search terms: TITLE-ABS (exoskeleton OR *suit OR weara* OR ortho* OR robot* OR garment OR device) AND TITLE-ABS (lift* OR squat* OR stoop*

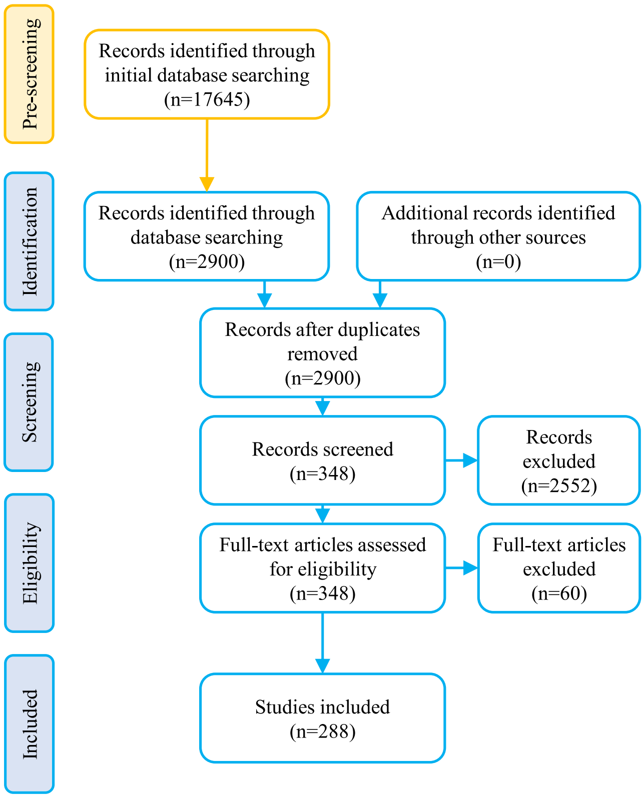

FIGURE 4. PRISMA flow diagram.

OR carry* OR handl* OR hold* OR bear* OR bend* OR walk* OR locomot* OR carriage) AND TITLE-ABS (augment* OR assist* OR support* OR transfer* OR reduce OR aid OR enhanc*) AND TITLE-ABS (pelvis OR limb OR *body OR *arm OR shoulder OR back OR spine* OR spinal OR torso OR lumbar OR hip* OR trunk OR waist OR knee OR extremity OR muscle). The search query was applied to the SCOPUS database and the search was limited to years from 2010 to 2022. The final search was done on July 03, 2023. The search query resulted in a total of 17,645 publications. The resulting data set was examined for co-occurrence of keywords and correlation among keywords. Keywords that are irrelevant to the study were identified and publications related to irrelevant keywords were excluded while updating the search query. The above process resulted in a total of 2,900 publications which were used for screening.

B. LITERATURE SELECTION AND CLASSIFICATION

Next, all the publications were screened using titles and abstracts. Literature on rehabilitative devices was excluded from the data set. Furthermore, literature containing assistive devices for rehabilitation, which is not explicitly designed for augmentation of load-carrying capability was excluded from the data set. Moreover, aids which do not resemble the loose definition of a robot such as backpack-like supports and posture correction belts were also excluded. Furthermore, the devices which only support body weight and the occupational exoskeletons which are developed to assist walking rather than manual handling work have also been excluded from this scoping review. This resulted in the removal of 2,552 records. The remaining 348 papers were first clustered according to the individual device. Thereafter, the following information was extracted from the literature to aid in further analysis.

- Body part of interest: Type (full body/ upper extremity/ lower extremity/ axial), Location of assistance (wrist/ elbow/ shoulder/ trunk/ hip/ knee/ ankle/ foot)
- Application (industry/ military/ consumer/ medical), Type of work (lifting/ carrying/ static holding)
- Information related to mechanical design: Mechanical structure (anthropomorphic/ non-anthropomorphic/ quasi-anthropomorphic), Material (rigid/ soft/ semi-rigid), Number of active DOFs, Number of passive DOFs
- Information related to powering mechanism: Principle of drive (active/ passive/ quasi-passive/ hybrid), Actuator (electric motors/ pneumatic actuators/ hydraulic actuators/ pneumatic muscle/ shape memory alloy/ series elastic actuators/ parallel elastic actuators), Power transmission method (direct drive/ cable-driven/ gear-driven/ linkage/ belt drive)
- Information related to control method: Control strategy (physical human-robot interaction/ cognitive human-robot interaction), Main control input (position/ motion/ force/ torque/ pressure/ muscle activity/ brain activity)

Classification of devices according to anthropomorphism has been adapted from previous literature [62]. Devices whose rotation axis of the joints is aligned with the human joints are classified as anthropomorphic, while devices which allow similar motions to humans without joint axis alignment are categorised as quasi-anthropomorphic. Devices which are not aligned with human joints and do not have similar motions are categorised under non-anthropomorphic devices.

IV. REVIEW

The results of the classification described in the previous section are presented in Table 2. These results are analyzed based on the application, body parts of interest, mechanical design, powering mechanism, control method, and methods of performance evaluation in the sub-sections that follow.

A. APPLICATION

This paper limits its scope to the power augmentation exoskeletons developed for non-disabled workers. Within this boundary, the analysis has identified several industries where these exoskeletons are consumable. Mostly, power augmentation devices are being used in industrial environments such as construction, manufacturing and logistics [63], [64], [65], [66]. These devices are also used in medical services such as care-taking where the weight of the patient has to be handled manually [67], [68]. Moreover, exoskeleton devices have been very popular in military use in the context of assisting soldiers to handle large weights on unfavourable terrains [69], [70], [71], [72].

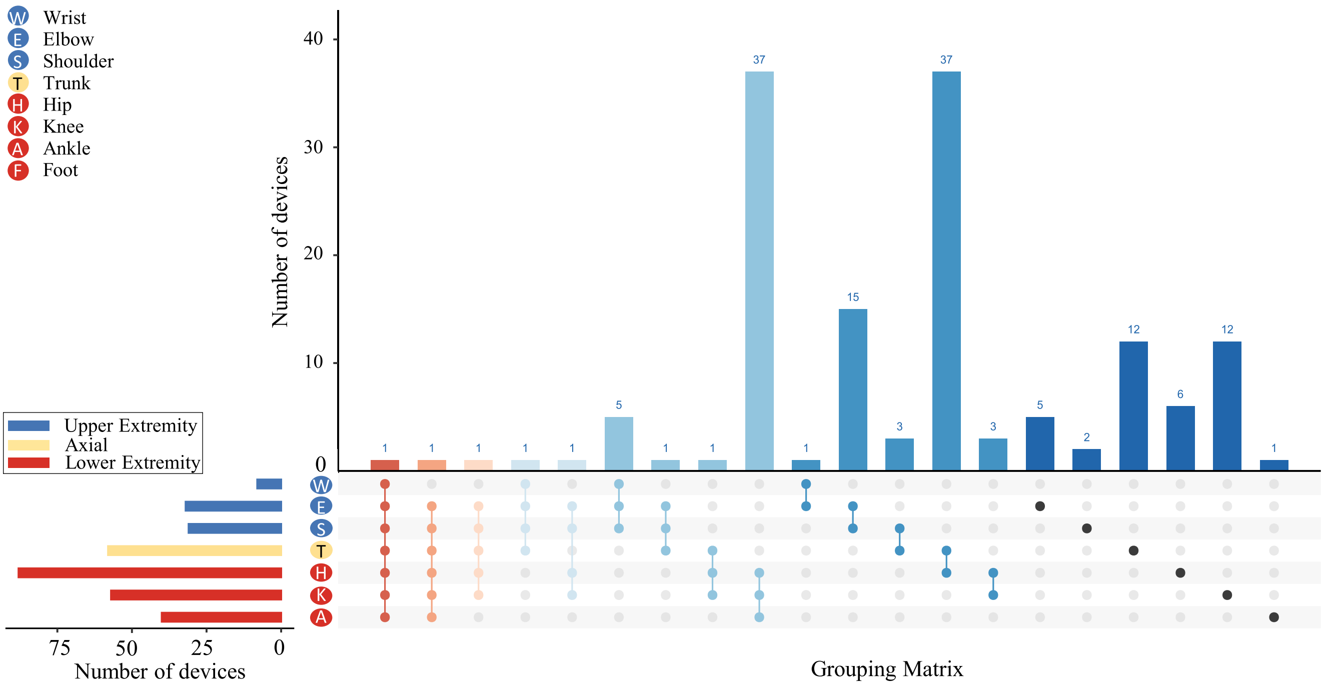

FIGURE 5. Assisting location upset plot - Relationship between the number of devices and assisting location of the exoskeleton: wrist, elbow, shoulder, trunk, hip, knee, ankle and foot. (The grouping matrix in the upset plot illustrates the intersections between each set using dots and connected lines. The rows in the matrix correspond to the sets, while the columns correspond to the exclusive intersections or aggregates. The vertical bars on top show the size of each intersection while the horizontal bars show the number of devices in each set.)

Overall, in most of these applications, employees have to deal with three types of work: lifting, carrying, and static holding. Figure 6 represents the statistics of devices which were designed for these three manual handling activities. Among many industrial environments, physical work involved in logistics mostly demands lifting and carrying activities. Here, the lifting tasks were identified using both stoop lifting and squat lifting methods. During the last seven years an exoskeleton named "RoboMate" was frequently involved in assisting the stoop lifting tasks [73], [74], [75], [76]. On the other hand, "XoR2" has been identified as an exoskeleton device that supports both squat lifting and load carrying in industrial environments [77]. In the manufacturing industries, especially in assembling and welding tasks, workers have to hold the loads either above the shoulder height, or below the waist in a bent posture. Exoskeleton devices such as "PAEXO" and "WSAD" have been developed to assist workers in these static postures [78], [79]. However, it is to be noted that the posture assistance devices that support only the bodyweight are not considered in this analysis [80]. In the majority of the military-based research attempts, soldiers were assisted by exoskeletons such as "K-SRD" in load carrying during their missions [81]. However, exoskeletons developed for combat and defence purposes were hardly noticed in the literature due to the confidentiality of military technologies.

B. BODY PARTS OF INTEREST

When studying the development of exoskeleton devices for manual handling activities during the past 12 years, it is evident that the anatomical segments and joints they assist correlate with manual handling tasks. Overall, the devices found in literature can be classified into three categories according to the regions of the body they support during manual handling. Thus, the devices can be classified as upper extremity, trunk (i.e. hip and back), and lower extremity. However, according to the analyses of power augmentation exoskeletons in the last 12 years, the most attention has been paid to assisting lower extremity parts, while second place is given to trunk assistance. Figure 5 shows the division of these devices according to the location of assistance and its connectivity.

Figure 6 shows the relationship between the number of devices and type of work which are lifting, carrying and static holding. From a biomechanical point of view, it is observed that the contribution of lower-extremity exoskeletons is primarily focused on load-lifting and load-carrying activities as shown in Fig. 6. In the case of static holding activities, the most significant work is done by the upper body. Thus, the lower-body exoskeletons which are developed for static holding activities are rarely noticed. The majority of hip and back-support exoskeletons have been developed to support load-lifting tasks during manual handling. These devices primarily focus on stoop lifting, due to the excessive

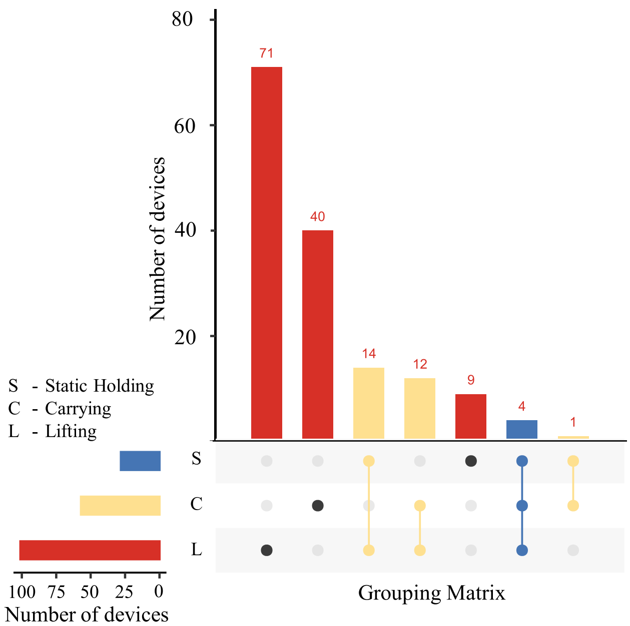

FIGURE 6. Type of work upset plot - Relationship between the number of devices and type of work: lifting, carrying and static holding supported by the exoskeleton.

burden on the postural muscles of the spine during stoop lifting.

As mentioned in section II of this article, the knee joint undergoes high stresses during load-carrying activities. Therefore, most of the devices that have been developed for load-carrying applications are designed either for the complete lower-extremity region or for the knee joint itself. However, in a few research attempts, the reduction of the burden on the trunk is also considered. When it comes to carrying, the task itself shows two basic patterns. Posterior load carriage is commonly supported with lower extremity exoskeleton [82] while anterior load carriage is assisted with upper extremity exoskeletons [83]. In anterior load carriage, the upper body biomechanics are for the most part similar to that of the static holding. Hence for this purpose, some upper extremity devices have been integrated with lower extremity devices to support load-carrying tasks. For example, [84] have developed full-body exoskeletons for this purpose.

Squat lifting is considered the best method to lift up an object from the ground level. In squat lifting, the knee joint gets a huge burden as same as carrying. Therefore, in literature, a cluster of lower extremity exoskeleton devices can be found that is developed for squat lifting [77], [85], [86], [87], [88], [89]. However, when it comes to the industry, there are instances that the workers cannot avoid stoop lifting during their work routine. Hence, a vast number of trunk-assisting exoskeletons has emerged and their effectiveness has been extensively analyzed for the stoop lifting tasks [65], [73], [90], [91], [92]. In the stoop lifting a huge load is acting on the hip joints and lumbar spine. To unburden the trunk, assist devices have been developed to provide additional torque when lifting up the trunk. However, occasionally, in some research, trunk assistance has been noticed even for the load carrying and load holding tasks [65], [90].

The exoskeletons on upper limbs are mostly developed for lifting up a load or keeping a load in a static position. Mostly the upper body devices for lifting and holding while carrying emerge in full-body exoskeletons so that the excessive weight can be grounded. Furthermore, these devices pay enhanced attention to the elbow joint. Static holding assistance during holding heavy objects above shoulder level, on the other hand, will be mostly dealt with using stand-alone upper body devices that focus on releasing the shoulder joint [78], [93].

C. MECHANICAL DESIGN

Power augmentation exoskeletons essentially exhibit creative structural implementations and actuation methods. The purpose of these implementations is to provide external power to the anatomical components or introduce additional artificial components to guide the force flow. Based on their structure, all the power augmentation devices can be divided into two categories as flexible and rigid. The rigid exoskeletons will comprise rigid links and rigid joints as their structural components. These links will guide the force flow to the ground bypassing wearers' anatomical parts. Furthermore, they transfer the supporting forces exerted by external actuators to the body parts. On the other hand, flexible exoskeletons comprise of flexible or elastic components providing comparatively higher freedom for the motions. These devices are also known as "Exo-Suites" [94], [95], [96].

As per the analysis, it is evident that the most frequently encountered type of exoskeletons are of rigid structures. However, in all three categories (upper extremity, lower extremity, and trunk), flexible exoskeletons have started emerging frequently in the second half of the last decade. Trunk exoskeletons have a comparatively large number of flexible exoskeletons while the upper and lower extremity devices occasionally employ flexible structures for their support.

Nevertheless, when analysing the nature of the mechanical structures for power augmentation exoskeletons, it was identified that all the rigid structures can also be classified as anthropomorphic, quasi-anthropomorphic, and non-anthropomorphic, based on their design.

In this review, the anthropomorphic type is defined so that the rotation axis of the exoskeleton joint is in alignment with the rotation axis of the human joint while the links in the structure are parallel with the anatomical limb segments. Anthropomorphic mechanisms can recreate similar movements to that of the wearers by mimicking all the degrees of freedom, thus allowing maximum mobility. However, there lies the practical difficulty of designing

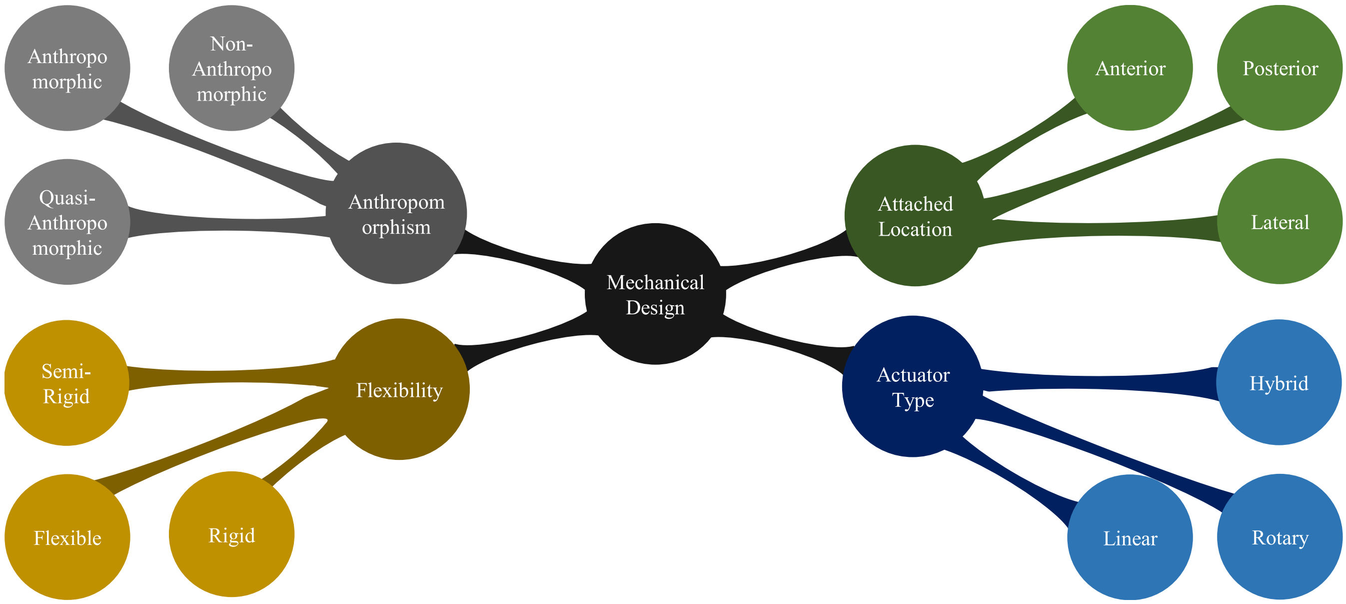

FIGURE 7. **Classification of the load handling exoskeletons based on their mechanical structure.**

mechanisms in which all the joint axes are in parallel to the natural axes to facilitate all the degrees of freedom. Some examples for anthropomorphic devices are [84], [89], [97], [98], [99], [100], [101], [102], and [103].

The quasi-anthropomorphic type is defined to have a joint functionally similar to the human joint, although the joint axes are not aligned. However, the links of quasi-anthropomorphic structures are in parallel with the anatomical limb segments. Albeit the joint structure is different, these devices are designed in such a way that they can create motions similar to the anatomical joints. A few quasi-anthropomorphic exoskeletons can be found in [104], [105], and [106].

In the non-anthropomorphic type, the relevant joint is not aligned with the human joints and links are not parallel to the human limb segments. However, the end effector of the non-anthropomorphic exoskeletons can still create the expected motion at the site of attachment of the device to the body, thus providing the expected mobility. The devices described in [70], [71], [83], and [107] can be listed as some examples of such devices.

During the analysis, the authors identified that the mechanical structure and overall appearance of these exoskeleton devices are comparable when they are designed to support the same body parts or to support similar tasks. Therefore, it is more suitable to discuss the mechanisms considering their classification based on the proposed location of support: i.e. upper extremity, lower extremity, and trunk. However, it should be noted that some devices have been developed to support multiple locations which falls under an intersection of the above categories. Furthermore, the upper extremity and lower extremity exoskeletons have fundamental similarities owing to the fact that they are developed to support limbs, unlike the trunk support devices. The statistical data of these classifications are represented in Fig.1.

1) MECHANICAL DESIGN OF BACK SUPPORT EXOSKELETONS

Most back/trunk support exoskeletons are developed as flexible devices which include compliant elements such as elastic actuators, cables, and pneumatic muscles that where attached posterior to the human body. These elements which can be either a single element or a few parallel elements, support the FL/EX of the spine as a whole. In literature, these devices are mostly labelled as power assist suites. For example, exoskeletons introduced in [66], [79], [102], [108], [109], [110], and [111] have been identified to discuss such designs.

Some rigid back support exoskeletons are also developed with compliant, posteriorly-placed elements [112]. However, a few devices have been developed mimicking the multi-jointed nature of the spine [113], [114]. Out of these devices, the Second Spine aids posterior load carriage by transferring loads bypassing the human spine [114]. Additionally, the non-anthropomorphic multi-jointed design in Exo-spine supports single DOF when load lifting [113].

Although the main supported DOF in the back support exoskeletons is the FL/EX motion of the spine, there are some devices which have been developed with the capability of twisting the trunk as well [67]. The second spine can support all three DOFs of the spine [114]. In some back support exoskeletons, instead of supporting the spine, the power at the hip joint is augmented with a trunk attachment [115]. Most of such devices support a single DOF which is the hip FL/EX. A majority of the back support exoskeletons are actively actuated, while some devices have adopted passively supported mechanisms as well [90], [116], [117], [118], [119].

The rigid devices that support the trunk can be identified as two major clusters based on the attachment of their rigid parts. Here, in most of the devices, rigid structures have been found to be attached behind the trunk, while a few of them are found with rigid attachments in the chest area. When the support structure is in the back or sides, generally, straps were used to attach the structure to the body [120]. However, in the chest support type, straps were not present [76].

2) MECHANICAL DESIGN OF UPPER EXTREMITY EXOSKELETONS

Upper extremity exoskeletons are usually employed in holding a heavy object at a static position or lifting. They can also be used to hold heavy objects while carrying them [83]. Some of them can be locked to facilitate power saving during the static holding activities [73]. In upper extremity exoskeletons, most of the reviewed designs were bulky with heavy rigid actuators [121]. However, since the second half of the last decade commercial devices such as Paexo [78] and H-VEX [93] have been noticed with light-weight, rigid structures to support static holding. Moreover, soft exoskeletons were occasionally identified in the upper limb assistance sector [122]. A major drawback of soft devices was that they have very low assistance capacity.

Upper extremity exoskeletons with rigid structures were mostly non-anthropomorphic designs [64] while some of them achieved anthropomorphic structures [123].

A majority of upper extremity devices developed in the past decade are active devices. However, there are a few devices which are fully passive [64], [73], [124], [125] or hybrid [126], [127], [128] as well.

Most active exoskeletons for the upper extremity are developed with anthropomorphic mechanisms. However, hybrid devices show a tendency towards quasi-anthropomorphic mechanisms, while passive devices are developed with a non-anthropomorphic tendency.

Several power transmission methods such as cable-drive, direct-drive, gear-drive, and linkages have been employed in upper extremity devices. The cable-drive mechanisms are more common than other power transmission methods. Passive devices show a high occurrence of direct-drive mechanisms. Gear-drive mechanisms can only be found in active devices. A very limited number of devices have linkage mechanisms as the power transmission method [73], [129].

Active upper limb devices are developed with one to five DOFs, while passive devices are mainly focused on providing a single DOF [64], [73].

3) MECHANICAL DESIGN OF LOWER EXTREMITY EXOSKELETONS

The lower extremity exoskeletons have been identified in both squat lifting and load-carrying tasks. Most of them were rigid and had anthropomorphic designs. For the most part, the structure of the lower extremity exoskeletons was similar. However, the most notable design differences were seen based on the actuation mechanism. Some of them have rotary actuators, such as electric motors or rotary elastic elements at the joints [98], [130] while some of them have linear actuators such as hydraulic and pneumatic actuators connecting the lower limb segments [106], [131]. The contribution of the rotary actuators is to parallel support the human joints while linear actuators bypass human joints when guiding load to the ground. Nevertheless, in literature, some devices were identified that completely disagree with the definition of anthropomorphic structures. Moonwalker [107] is a good example of this category. Another notable structure type was lower extremity exo-suites [132] which were categorised as flexible devices.

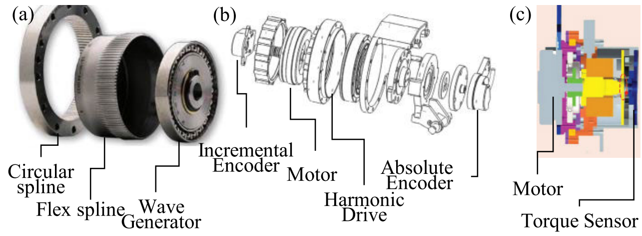

FIGURE 8. Harmonic drive power transmission systems (a) Harmonic drive gear, (b) Actuator design of Exoskeleton robot for steel manufacturing (adapted from [92]), (c) Actuator design – Lower back robot exoskeleton (adapted from [135]).

Actively controlled exoskeletons are very common in lower extremity devices. Nevertheless, a few passive exoskeletons have also been developed during the past decade [89], [133]. A majority of active lower extremity exoskeletons have been developed by preserving the anthropomorphic features, while among passive devices, non-anthropomorphic mechanisms take a significant place [133], [134].

Although mechanisms such as cable-drive, direct-drive, gear-drive, and linkage mechanisms are employed in lower extremity devices, the direct-drive method is the most common power transmission method that can be seen in active, passive, and hybrid devices, all alike.

D. POWERING MECHANISM

1) ELECTRICAL ACTUATION

Most of the exoskeletons developed for load lifting have used electric motors (AC, DC, Brushless DC, Servo) for actuation. The actuation unit is designed as a single unit and placed aligned to the hip joint rotation axis for the actuation. The actuation unit is comprised mostly of the motor, gear reducer, and sensors.

The devices like Active Trunk - Robo.Mate [73], [74], [75], [76], [120], [136], [137], [138], [139], [140], [141], [142], [143], Exoskeleton for steel manufacturing [92], Cyberdyne – HAL 5 [144], [145], [146], [147], and Industrial Handling Augmentation for Spinal Support have used electrical motors in conjunction with strain wave gear (Harmonic Drive reducers-HD) to achieve the required amplification of torque. Due to the lower torque of electric motors (less than 1 Nm), HDs have been used to achieve extreme gear reductions of 100:1. HDs have the added advantage of lower back drivable torque, higher efficiency, high torsional stiffness, zero backlash, high torque capacity compared to other gear reducers such as planetary gear drives, worm gear drives. The actuator is coupled with an encoder/ torque sensor for angular and torque measurements required for the control system and is enclosed as a single unit. In Industrial Handling Augmentation for Spinal Support apart from electric motors and gear drives, a clutch has been used to engage and disengage the transmission from the human body. This allows the wearer to cut off the existing back driving torque when not in a lifting position [12], [142].

Exoskeletons with electric motors have used the series and parallel elasticity to add the required compliance and save energy. Several studies have been done on the effectiveness of parallel elastic actuators (PEAs) on the reduction of the overall motor effort, and the effect of series elastic actuators on providing required compliance to a joint.

SEA has been used in the Parallel-Series Elastic Actuator design for lower limb exoskeletons by researchers at Harbin Institute of Technology. In Active Trunk by Robo-Mate, the Bungee cord has been used as the parallel spring where it is deflected to store energy while bending. The exoskeleton developed by Jawad Masood et al. contains PEA made of an elastic cord made of natural rubber elastomer to store energy while lowering and release energy during lifting. The use of PEA has reduced the overall weight of the exoskeleton by 20% and torque limitations.

Active Back-Support Exoskeleton was developed to reduce the risk of injuries and musculoskeletal disorders during manual material handling activities [148]. It consists of two joints to support lumbar and hip motions. The structure is made of three links and straps are used to attach the device on the wearer's shoulders, waist and thighs. Authors claim that the device has four DoFs in total to facilitate FL/EX and AB/AD at lumbar and hip joints. Two SEAs were used to provide assistance during lowering and lifting loads and the overall system weighs approximately 4.4 kg excluding the controller and power supply. SEAs were constructed using a BLDC motor with ball screw transmission and serial spring arrangement. A Bowden cable is then used to transmit torque to the hip joint. The effectiveness of the active back-support exoskeleton was determined using multiple test subjects (nos 11). Results showed a notable reduction of the normalized RMS EMG activity of both left and right erector spinae muscles. The mobility test indicated a notable reduction in walking speed when wearing the exoskeleton. However, the Borg scale evaluation indicated an averaged perceived exertion level when using the exoskeleton.

2) PNEUMATIC ACTUATION

Exoskeletons developed for load-lifting applications with pneumatic actuators were limited compared to exoskeletons with electric actuators. Different actuation methods have been

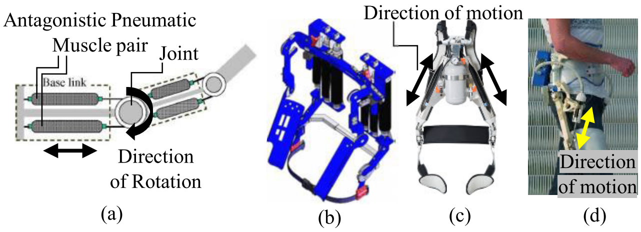

FIGURE 9. Pneumatic Actuation mechanisms: (a) Antagonistic pneumatic muscle joint (adapted from [149]), (b) Muscle suit actuation system by Tokyo University of Science(adapted from [150]), (c) Muscle Suit (Commercial version) by Innophys, (d) Pneumatic cylinder joint actuation in HiBSO (adapted from [151]).

proposed with exoskeletons and are developed with McKibben artificial muscles and pneumatic cylinders. McKibben muscles have been used as antagonistic spring pairs to achieve desired torque and positions [149]. Muscle suit is an exoskeleton developed with pneumatic actuators- McKibben muscles. Muscle suit is developed evolving into several versions and to a commercial product [150]. Muscle suit is activated by pressurising the pneumatic muscles thereby affecting the lumbar curvature to reduce in a lifting stance.

Hip Ball Screw Orthosis (HiBSO) is an active orthosis designed to assist the hip flexion-extension of the elderly. Although HiBSO doesn't fall into the power augmentative category HiBSO is designed to assist in lifting. A pneumatically actuated cylinder is used to assist in flexion and extension [151].

Muscle Suit developed by Tokyo University of Science is capable of providing lower back support to reduce muscle usage and fatigue during load lifting [152]. The two variants of the Muscle Suit are referred to as the standard model and the standalone model. The standard model uses two McKibben-type soft pneumatic actuators to generate the assistive force. A single artificial muscle weighs only 130 g and can generate 2,200 N force using a supply of 0.5 MPa compressed air. Other key hardware components included in this system include an air compressor, air cylinder, solenoid valve, switches and sensors. The breath-activated switch and touch sensor switch on the chest were used to control the valve during operation. The overall weight of the standard model is 5.5 kg, and a pulley and wire mechanism is used to apply an assistive torque on the upper body with respect to the thigh. Authors claim the system is capable of reducing the lower back and the legs during lifting and lowering loads as it can deliver an assist force of 30 kgf. However, the authors indicate difficulties in manually operating the switches and correctly detecting the motion intention of the wearer. The bulkiness of the system has also caused notable hindrances. The standalone model uses the same setup with the actuators pressurised to an initial pressure when standing upright. Importantly, the pneumatic muscles operate without receiving compressed air externally, thus they act as springs when the wearer bends during lifting operations. The maximum output torque generated by the standard and standalone models is approximately 140 Nm and 100 Nm respectively. The effectiveness of each model was evaluated using EMG activity. Results of the multiple test subjects (nos 4) who participated in the lifting experiments indicated a notable reduction of muscle activity in the lumbar region. In addition, the dynamic length of body sway during repetitive lifting was found to be lesser when wearing the muscle suit. However, the assistive effect of muscle suits on reducing fatigue has not yet been investigated.

The soft pneumatic elbow exoskeleton, named 'Carry' was developed to assist the elbow during carrying and holding loads [153]. The target was to reduce muscle fatigue and the risk of injury. Carry has a soft human-machine interface and includes a soft pneumatic actuator that can provide 7.2 Nm torque to the elbow. Carry has a weight of 1.85 kg, and this includes the actuator made with a TPU bladder encased by a textile tube. Upon pressurization, the tube inflates and the elbow gets extended. Textile straps with plastic buckles are also used to minimize slipping effects. However, the required pneumatic pressure was supplied using a stationary compressor by a tethered means. The effectiveness of the elbow exoskeleton was evaluated using multiple test subjects (nos 12). The experiments conducted with Carry resulted in a reduction of muscle activity by 50% and a reduction of net metabolic rate by 61%. Authors also claim that Carry has successfully reduced muscle fatigue and has the potential to reduce joint degeneration and pain during material handling work.

3) HYDRAULIC ACTUATION

Hydraulic actuation methods were limited to exoskeletons developed for load lifting. Due to the high complexity and problems with mounting hydraulic circuit components in the human body developments were limited. XOS2 is a full-body exoskeleton developed to augment strength using high-pressure hydraulics. Due to the high power ratios of the actuation mechanism wearer could lift 50 lbs with each arm. Due to the high-pressure hydraulics exoskeleton has to be tethered to operate, which in return is a drawback in portability.

4) PASSIVE ACTUATION

Several passive actuation methods were proposed in exoskeletons developed for load lifting. Passive actuation is based on elastic elements that store energy while lowering the body and releasing it during the lift. Passive actuation mechanisms do not require an external power source therefore developed exoskeletons were lightweight although assistance and control were limited.

Personal lift assistive device (PLAD) [154] was designed to support the lower back during lifting tasks. PLAD uses two elastic ropes extending from knee joints on either side to the shoulders via the back of the human body. During lifting tasks, elastic cords extend and contract to reduce the lumbar moment. The exoskeleton with flexible beams provided passive actuation using the bending of flexible beams. Energy is stored in the leaning and released during lifting [155].

A biomechanically assistive garment has also been developed to assist in load lifting. The actuation mechanism used was elastic bands acting parallel to lower back extensor muscles providing extension moment about the hip joint. The garment consisted of a shirt (upper body), shorts (lower body and elastic bands connecting the shirt and shorts. With the proposed passive actuation mechanism garment reduced erector spinae muscle activity by 23-43% [156].

The industrial passive assisted exoskeleton or IPAE was developed with the intention of reducing disorders caused by lifting operations on the lower back and arm muscles [157]. It mainly consists of a back support frame, waist elastic units, leg supports, and strap units for the shoulder and waist. Authors claim that the device can be worn like a backpack, and the total weight of the system is only 4 kg. In order to improve the comfort of the wearer, all surfaces of the device are covered with flexible fabrics and can be closely fitted to the body. However, the donning process requires assistance and takes about 2 minutes duration. The waist elastic elements are energized during the lowering phase of the stoop lift cycle, and subsequently released during the upward phase to relieve the lower back muscles. The device also includes hooks and straps connecting the wrists and shoulders for reducing the loading on the arm muscles when handling the load. The effectiveness of the system was evaluated by multiple test subjects (nos 8). The EMG activity of the lower back muscles was investigated using portable EMG sensors. In addition, oxygen consumption was also measured using VO2 sensor equipment. A toolbox with weights inside was used for carrying out stoop lift tasks from the ground to a table at waist height. The local perceived pressure, perceived exertion, and system usability were also evaluated using well-documented methods published in the literature. Experiment results have indicated that IPAE is capable of reducing muscle activities of both the lower back and upper arms during lifting works. Interestingly, IPAE did not notably influence oxygen consumption during repeated lifting. The rate of perceived exertion with or without the IPAE also showed no significant difference. The local perceived pressure was significantly higher for the shoulder and wrist. Interestingly, only 50% of the subjects rated IPAE as having acceptable usability. Although IPAE can significantly reduce muscle fatigue of the lower back and upper arm, the authors recommend not to increase the workload, worktime, or working frequency for workers equipped with IPAE.

The passive upper-extremity exoskeleton suit or PUES was developed to reduce the muscle efforts of the right arm during static and dynamic tool holding operations [158]. The goal was to decrease the fatigue and possible WRMSDs during high-intensity repetitive installation works. The device consists of two parts, namely the exoskeleton body and the passive gravity balance arm. In total PUES weighs approximately 3.1 kg. On one part, the exoskeleton body is responsible for carrying loads and tools while providing freedom for movement. On the other part, the arm attached to the hip of the exoskeleton is used to mount the handheld tool. Here, the passive mechanism of the arm is designed to maintain the balance within a predefined range of activity and is able to able to handle different weights. Moreover, the handheld tools attached to the arm can be moved or suspended vertically and have been shown to dampen vibration. The arm mechanism uses gas springs coupled to parallelogram structures. However, counterweights are also used on the sides to balance the moment caused by the mass of the tool and arm structure. The exoskeleton has 12 joints that are responsible for transferring the weight of the overall system to the ground. The effectiveness of PUES was evaluated by measuring the EMG activity of the arm with multiple test subjects (nos 10). Both static and dynamic load tests were conducted to ascertain the effects on arm muscles when wearing PUES. Results indicate a notable reduction of normalized root mean square EMG and mean power frequency for biceps and deltoid for both static and dynamic tests. PUES shows potential to reduce the strain on the human upper arm but has limited functionality because of its bulky and complex structure. Moreover, the authors have yet to investigate the influence on energy consumption.

The passive exosuit with body-powered variable impedance has been designed to correct the lifting posture by immobilizing the vulnerable joints [159]. The authors aim to use this novel approach to prevent back injuries caused by repetitive lifting. The exosuit adds impedance to the human joints to discourage stooping motion based on how far the wearer's movements are from squat lifting trajectories. This is achieved by including an artificial biarticular tendon in exosuit. By placing the artificial tendon across two joints, it helps couple the angle of rotation of each joint. When one joint is restrained, it restricts the rotation of the other joint. In order to modulate the tendon impedance, the authors used an ingenious non-mobile mechanism, an A-shaped tendon structure. Here, the tendon force depends on the state angle of the triangular formation of a rubber band and cables. When the wearer abducts the hips during squat lifting, the rubber band attached to the cables routed behind the knees get stretched, increasing the state angle and this allows the cables running through the hip to the shoulder to be pulled with lesser force. However, during stoop, since knees remain closer to each other, the state angle is lower and the shorter rubber band possesses higher resistance. Accordingly, during squatting action, the suit creates a lower impedance to movement, whereas during stooping action a higher impedance. Authors also claim that the design of the suit allows the wearer to generate various movements such as kneeling comfortably without noticeable resistance. The effectiveness of the exosuit was evaluated with multiple test subjects (nos 10). During squat lift experiments, joint positions were measured using a motion capture system, and

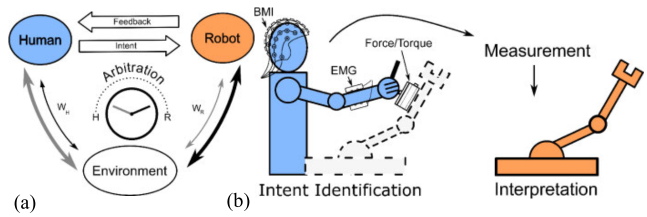

FIGURE 10. Human Robot Interaction (adapted from [161]) (a) A framework for human-robot information exchange and interaction with the environment, (b) Conveying of human's intent - Identification, Measurement, Interpretation.

metabolic gas data using a potable respiratory gas analyzer. Results revealed the suit is effective in promoting squat posture over stoop posture. However, the metabolic rate when using the suit is marginally better, and the statistical results show no significant difference. Similarly, the back compressive force from calculations shows a marginal decrease and no significant difference as per the recorded results by the authors. A notable limitation of the passive exosuit is its nature to constrain forward-leaning motion, making it more uncomfortable for the wearer to perform non-lifting motions. The authors have proposed a control module to permit free motion when needed.

The HeroWear Apex is a passive back-assist exosuit developed to reduce biomechanical loads on the back [160]. The upper part of the suit is similar to a backpack and has two elastic bands connected to the two thigh sleeves. It is 1.5 kg in weight and the switch is used to engage or disengage the assistive mechanism. When engaged, elastic bands will stretch as the wearer bends forward, and this generates an assistive torque about the lumbar spine during the upward phase of stoop lifting. Here, the elastic bands with different stiffnesses can be included depending on the wearer's preference. Multiple test subjects (nos 20) participated in experiments conducted to evaluate the effectiveness of the device. EMG activity of the muscles on the back, trunk kinematics, and heart rate measures were recorded during the tests. Authors claim that the exosuit was able to reduce the EMG activity by 15% during lifting and lowering tasks. The exosuit also affected the kinematic of the trunk, in particular, it reduced the trunk FL/EX ROM. Participants also reported that the exosuit was mild to moderately helpful in carrying out the lift operations.

E. CONTROL METHOD

Controlling methods based on human intention identification can be recognised in much of the literature.

1) INTENT DEFINITION

The human body is itself a control system that shares information between its subsystems. Subsystems that share information could be divided into central nervous system, peripheral nervous system and musculoskeletal system. Each sub-system contributes to the intention and motion of humans and can be defined with measurable physical quantities. Each defined physical quantity could be taken input variable for the exoskeletal system.

2) INTENT MEASUREMENT

Intent measurement is based on the identified quantity. Considering the subsystem different methods, and tools such as electroencephalography (EEG), electromyography (EMG), and force and torque measuring are used.

3) INTERPRETING INTENT

Measured intent could be interpreted as binary, hexadecimal and other data, converted parameters. Human intention identification could be divided into two main categories: physical human-robot interaction (pHRI) and cognitive human-robot interaction (cHRI) [128]. pHRI refers to the connection between the exoskeleton and humans generated using the physical contact between the exoskeleton and the human (musculoskeletal system) [161]. cHRI refers to connection generated through changes in the central nervous system. Sensors used in pHRI are position and motion sensors, Force and pressure sensors [135]. Sensors used in cHRI are muscle activity sensors and brain activation sensors [128].

F. METHODS OF PERFORMANCE EVALUATION

One of the most important aspects of developing occupational exoskeletons is the evaluation of their performance. Validating that the exoskeletons provide the expected support and motion in manual handling can be used as a measure of effectiveness from the performance point of view. When observing past research publications, several methods of performance evaluation are noticeable.

Some researchers have used metabolic cost as an indication of the performance of the devices. Analyzing of the volume and composition of the breathing gas of wearers will provide information on the rate of oxygen-carbon dioxide conversion that happens inside the cells which ultimately indicates the effort that a person's body should make when performing a manual handling task [132], [162], [163].

Electromyography (EMG) is used as another method of performance evaluation. Measurement of muscle activities when using an occupational exoskeleton can demonstrate the forces exerted by individual muscles/muscle groups themselves. This will show the degree of support provided by the device since an effective exoskeleton would indicate a lower muscle activity in the relevant muscles of the wearer. Depending on the manual handling task, the joint that is supported, and the motion assisted by the exoskeleton, the selection of the muscles/muscle groups for EMG analysis varies [69], [126], [132], [133], [163], [164].

Examining the muscle work with and without the exoskeleton is another method that has been employed to evaluate some devices. This is generally performed by measuring the torques and angular velocities of the joints [165].

Some exoskeletons are subjected to kinematic analysis to evaluate the kinematic conformity of the devices to the natural movements. While some analysis techniques use sensory data from sensors such as inertial measurement units (IMU) and accelerometers, the use of motion capture analysis can also be seen in some cases. Such methods will indicate whether the wearer of the exoskeleton can move conforming to the naturally expected motions [132], [133], [163].

When evaluating the performance, the common practice in many devices has been to compare one or more performance indicators of human subjects when performing a manual handling task with and without the exoskeletons. The number of subjects and the degree of repetition of the task vary.

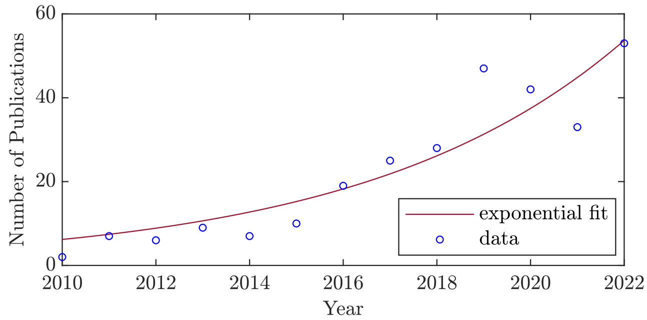

FIGURE 11. Scatter-plot showing the number of publications, each year. Exponential fitting of the data revealed an increase in the number of articles written between 2010 and 2022 ($r^2 = 0.94$).

V. BIBLIOMETRIC ANALYSIS

Bibliometric analysis provides insight into the research trends using statistical techniques. Keyword co-occurrence networks (KCN) and article co-citation networks (ACN) can be used as effective ways of knowledge mapping [285] and visualize knowledge base in a specific field of research. This section exploits the screened data set of literature from the SCOPUS database and uses R-package bibiliometrix [286] for the analysis.

The screened data set was fed into R and was converted into an R data frame prior to the analysis. Out of 288 articles in the data set, the majority of the articles were published by corresponding authors in China (32 articles, 20.92%), Korea (25 articles, 16.34%), USA (22 articles, 14.38%), Japan (16 articles, 10.46%) and Italy (13 articles, 8.50%). 288 articles were distributed among 156 journal articles, 9 book chapters and 123 conference papers. The most relevant sources for the publications were Applied Ergonomics (10 articles), IEEE Robotics and Automation Letters (10 articles), Proceedings of the IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (9 articles), Proceedings of IEEE International Conference on Robotics and Automation (8 articles), and Biosystems and Biorobotics (7 articles). Publications had a high collaboration index with 4.97 authors per document.

During the past 12 years, the number of publications related to manual handling exoskeletons has gradually increased. Temporal analysis shows that the publication count

TABLE 2. Exoskeleton classification from 2010 to 2022.

Name (Research Stage[a])	Year	Body Part		Application	Mechanical Design			Powering Method		Control		Testing	Reference
		Type[b]	Assist. Location[c]	Work Type[d]	Structure[e]	Weight[f]	DoF[g]	Drive[h]	Actuator[i]	Strategy[j]	Main Input	Payload	
ELEBOT(P)	2010	LB	HKA	C	R/Q-An	31	1/6	H	C/PA	pHRI	Force	30	[106]
MoonWalker(P)	2010	LB	HKA	C	R/N-An	n.s.	1/0	Q-P	R/EM	pHRI	Force	32	[107]
NES-3(P)	2010	LB	HKA	C	R/An	n.s.	2/5	H	R/EM	pHRI	Force	30	[166]
Kogakuin Uni. (b)*(P)	2011	UB	TH	L	R/Q-An	n.s.	2/0	A	R/EM	cHRI	Muscle Act.	n.s.	[67]
PLAD(P)	2011	UB	TH	LS	F/Q-An	n.s.	0/2	P	C/-	pHRI	Motion	25	[108]
Muscle suit(P)	2011	UB	WESTH	LS	R/Q-An	9.2	5/6	H	C/PM	pHRI	Pressure	20	[126]
Power Assist Suit(P)	2011	FB	ESHK	L	R/An	40	4/4	H	C/PA	pHRI	Position	10	[85]
Body Extender(P)	2011	FB	WESTHKA	L	R/An	160	22/0	A	R/EM	pHRI	Force	101.94	[84]
exo-spine(P)	2011	UB	T	LS	-/An	n.s.	1/0	H	R/EM	cHRI	Muscle Act.	n.s.	[113]
Back support muscle suit(P)	2012	UB	TH	LC	R/An	5.5	2/0	A	C/PM	pHRI	Pressure	30	[167]
Toyota Technological Inst.*(P)	2012	FB	ESTHKA	LS	R/Q-An	n.s.	4/2	H	R/EM	pHRI	Motion	5	[127]
KAERI, South Korea (a)*(P)	2012	LB	HKA	C	R/Q-An	n.s.	2/4	H	R/EM	pHRI	Position	40	[168]
KSRD/Dermoskeleton(Cm)	2012	LB	K	LC	F/n.s.	0	0/0	-	R/EM	-	0	50	[69]
Hanyang Uni. (d)*(P)	2012	UB	ES	LCS	R/An	n.s.	6/2	H	-/-	pHRI	Force	10	[128]
UESTC*(P)	2012	LB	K	C	R/Q-An	n.s.	2/0	A	R/HA	pHRI	Position	30	[169]
Kogakuin Uni. (a)*(P)	2013	UB	TH	L	R/N-An	15	2/2	H	R/EM	cHRI	Muscle Act.	n.s.	[68]
Harbin Inst. of Tech. (c)*(P)	2013	LB	HKA	C	R/An	0	0/0	-	-/-	-	0	40	[170]
NUDT, Changsha*(-)	2013	UB	WES	L	R/Q-An	n.s.	5/0	A	R/HA	pHRI	Pressure	30	[121]
Michigan Techno. Uni.*(P)	2013	LB	K	LC	R/N-An	n.s.	1/0	A	C/PM	cHRI	Muscle Act.	n.s.	[86]
XoR2(P)	2013	LB	HKA	LC	R/An	20	6/8	H	R/PA	pHRI	Pressure	30	[77]
Power assist wear(P)	2013	UB	TH	L	F/n.s.	0.8	2/0	A	C/PM	pHRI	Position	12.6	[109]
Hanyang Uni. (b)*(P)	2013	LB	HKA	C	R/Q-An	n.s.	6/0	Q-P	R/EM	pHRI	Force	n.s.	[171]
WAD(P)	2013	UB	T	S	F/n.s.	1.5	0/1	P	C/-	pHRI	Motion	15	[66]
WSAD(P)	2013	UB	T	L	F/n.s.	0.6	2/0	A	R/EM	pHRI	Position	n.s.	[79]
SJTU-EX(P)	2014	LB	HKA	C	R/N-An	n.s.	6/0	A	-/HA	n.a.	n.a.	70	[172]
The Second Spine(P)	2014	UB	T	C	R/An	1.8	3/0	A	C/EM	pHRI	Motion	22	[173]
Hanyang Uni. (a)*(-)	2014	LB	K	LC	R/An	n.s.	2/0	A	R/HA	-	0	10	[103]
Zhejiang Uni.*(P)	2014	UB	E	LS	R/An	2.1	1/0	A	C/PM	cHRI	Muscle Act.	n.s.	[129]
MIT (a)*(P)	2014	LB	A	C	R/N-An	4	2/0	A	R/EM	pHRI	Force	23	[70]
LAFMIA UMI 3175(*a*)*(-)	2014	UB	T	L	R/N-An	n.s.	1/2	A	C/PM	pHRI	Force	n.s.	[112]
Selçuk Uni.*(P)	2014	LB	HKA	C	R/An	n.s.	4/6	A	R/HA	pHRI	Force	n.s.	[174]
UST, Ansan*(P)	2014	LB	HKA	C	R/An	n.s.	4/8	A	R/HA	pHRI	Motion	20	[175]
Robo-mate(-)	2015	UB	TH	L	R/N-An	11.64	2/0	A	-/EM	pHRI	Position	40	[73]–[76], [120], [136]–[143]
ADD, South Korea (b)*(P)	2015	LB	HKA	C	R/An	n.s.	4/0	A	-/HA	pHRI	Force	45	[105], [176]
HUALEX(P)	2015	LB	HKA	C	R/An	15	4/0	A	-/EM	pHRI	Force	40	[101], [177]
HEXAR-CR50(P)	2015	LB	HKA	C	R/Q-An	23	2/4	H	-/-	pHRI	Force	30	[104], [178]

TABLE 2. ***(Continued.)*** **Exoskeleton classification from 2010 to 2022.**

Name (Research Stage[a])	Year	Body Part		Application	Mechanical Design			Powering Method		Control		Testing	Reference
		Type[b]	Assist. Location[c]	Work Type[d]	Structure[e]	Weight[f]	DoF[g]	Drive[h]	Actuator[i]	Strategy[j]	Main Input	Payload	
Chuo Uni. (a)*(P)	2015	UB	TH	L	F/n.s.	6.2	0/1	P	-/PM	n.a.	n.a.	15	[110], [116]
HIT-LEX(P)	2015	LB	H	C	R/An	n.s.	0/4	P	-/-	n.a.	n.a.	n.a.	[89], [102], [179]
KAIST, UTRCEXO*(P)	2015	LB	HKA	C	R/An	29.5	2/0	A	-/EM	pHRI	Force	10	[130]
POSCO Tech. Res.h Lab.*(P)	2015	UB	TH	L	R/An	n.s.	2/0	A	-/EM	pHRI	Torque	30	[92]
LAFMIA-UMI 3175(*b*)*(P)	2015	LB	TH	L	R/N-An	n.s.	4/0	A	-/PM	pHRI	Pressure	n.s.	[180]
UMass Amherst*(P)	2015	LB	TH	L	F/n.s.	3	0/1	P	-/-	n.a.	n.a.	n.s.	[181]
Uni. of Tsukuba*(P)	2015	FB	WESTH	S	R/Q-An	n.s.	0/0	A	-/EM	-	0	0	[182]
Tokyo Inst. of Tech.*(P)	2015	UB	TH	L	F/n.s.	n.s.	0/2	P	-/PM	n.a.	n.a.	10	[183]
Harvard Uni. (f)*(P)	2016	LB	H	C	F/n.s.	n.s.	2/0	A	C/EM	pHRI	Motion	23	[184], [185]
Harvard Uni. (a)*(P)	2016	LB	HA	C	F/n.s.	6.6	6/0	A	C/EM	pHRI	Force	23	[95], [132], [184], [186], [187]
Chuo Uni. (c)*(P)	2016	LB	K	L	F/n.s.	n.s.	2/0	A	C/PM	n.a.	n.a.	15	[188]–[190]
NIT, Tsuyama College (b)*(-)	2016	UB	TH	L	F/n.s.	n.s.	1/0	A	C/PM	cHRI	Muscle Act.	n.s.	[111], [191], [192]
Toshiba Corporation*(P)	2016	LB	K	L	R/Q-An	10	2/8	A	R/EM	n.a.	n.a.	20	[88]
Uni. of Fukui*(P)	2016	LB	HKA	C	R/N-An	n.s.	4/2	A	R/EM	pHRI	Motion	n.s.	[193]
Harbin Inst. of Tech. (g)*(P)	2016	LB	HKA	C	R/An	n.s.	4/4	A	R/HA	pHRI	Motion	n.s.	[194]
LEPEX(-)	2016	LB	HKA	C	R/An	n.s.	6/8	A	-/-	n.a.	n.a.	75	[195]
Nazarbayev Uni.*(-)	2016	LB	HKA	C	R/An	n.s.	8/0	A	R/EM	pHRI	Force	n.s.	[196]
HeSA(P)	2016	UB	TH	C	R/An	2.95	2/4	A	R/EM	pHRI	Position	18	[197]
Laevo(Cm)	2016	UB	TH	LS	R/An	n.s.	0/2	P	C/S	n.a.	n.a.	n.s.	[76], [90], [163], [164], [198]–[200]
Uni. of Twente*(P)	2016	UB	EST	LS	R/N-An	n.s.	0/n.s.	P	n.a./n.a.	n.a.	n.a.	11.5	[125]
Harbin Inst. of Tech. (a)*(-)	2017	LB	THKA	C	R/An	n.s.	4/9	A	R/EM	pHRI	Force	50	[201], [202]
Uni. of Pisa*(P)	2017	UB	E	S	F/n.s.	2.2	2/0	A	R/EM	pHRI	Position	n.s.	[203], [204]
Yamaguchi Uni.*(P)	2017	UB	E	LS	R/An	n.s.	2/0	A	R/PM	pHRI	Force	5	[205]
VUB*(P)	2017	LB	H	L	R/N-An	4.8	0/6	P	n.a./n.a.	n.a.	n.a.	n.s.	[206]
Seoul National Uni.*(P)	2017	UB	S	S	F/n.s.	n.s.	n.a./0	A	-/-	n.a.	n.a.	2	[124]
Tokyo Uni. of Sci.*(P)	2017	UB	ST	L	R/An	6.5	4/6	A	R/PM	pHRI	n.a.	10	[207]
Japan Automobile. Res. Inst.*(P)	2017	LB	TH	L	R/An	15	1/0	A	R/EM	pHRI	Position	55	[91]
ADD, South Korea (c)*(P)	2017	LB	HKA	C	R/An	n.s.	4/10	A	R/EM	pHRI	Force	n.s.	[82]
ECUST, China (b)*(P)	2017	LB	K	C	R/An	20	2/2	H	R/HA	pHRI	Force	60	[179]
Mie Uni.*(-)	2017	UB	TH	S	F/n.s.	n.s.	0/1	P	C/EB	n.a.	n.a.	n.s.	[208]
Harbin Inst. of Tech. (e)*(P)	2017	LB	HKA	C	R/An	30	2/12	H	R/HA	pHRI	Force	35	[131]
Fraunhofer IPA*(P)	2017	UB	ES	LCS	R/N-An	n.s.	2/8	H	R/EM	pHRI	Force	n.s.	[209]
Uni. of L'Aquila*(P)	2018	UB	TH	L	R/An	n.s.	2/0	A	C/PM	cHRI	Muscle Act.	25	[210]
Anthro-X(P)	2018	LB	HKA	LC	R/An	21.4	4/6	A	R/EM	pHRI	Position	n.s.	[98]
APO(P)	2018	UB	TH	L	R/An	n.s.	2/0	A	n.s./EM	pHRI	Motion	5	[211], [212]

TABLE 2. *(Continued.)* Exoskeleton classification from 2010 to 2022.

Name (Research Stage[a])	Year	Body Part		Application	Mechanical Design			Powering Method		Control		Testing	Reference
		Type[b]	Assist. Location[c]	Work Type[d]	Structure[e]	Weight[f]	DoF[g]	Drive[h]	Actuator[i]	Strategy[j]	Main Input	Payload	
Vanderbilt Uni.*(P)	2018	UB	TH	L	F/n.s.	2	0/n.a.	P	C/EB	n.a.	n.a.	24	[156]
E-ROWA(P)	2018	LB	HKA	C	R/An	9	2/10	H	R/HA	pHRI	Position	35	[213]
EXHAUSS Stronger(Cm)	2018	UB	WES	LCS	R/N-An	9	0/2	P	C/S	n.a.	n.a.	15	[64]
Exobuddy(P)	2018	LB	HKA	C	F/n.s.	21.8	2/n.s.	Q-P	R/HA	pHRI	Force	36	[71]
IIT, Chennai*(-)	2018	LB	HKA	S	R/An	n.s.	6/4	A	R/-	n.a.	n.a.	30	[214]
HAL(P)	2018	UB	TH	L	R/N-An	n.s.	1/0	A	R/EM	cHRI	Muscle Act.	12	[144]–[147]
HUALEX2(P)	2018	LB	HKA	C	R/An	n.s.	6/8	A	R/HA	pHRI	Force	25	[215]
North Carolina State Uni.*(P)	2018	LB	TH	L	R/An	11.2	4/1	A	C/SEA-PEA	pHRI	Pressure	25	[135]
PLL-01(P)	2018	LB	HKA	C	R/N-An	n.s.	4/2	A	R/EM	pHRI	Motion	n.s.	[216]
NIT, Tsuyama College (a)*(P)	2018	UB	WES	CS	R/N-An	7.4	2/0	A	R/EM	pHRI	Motion	3	[83]
Chuo Uni. (g)*(P)	2018	LB	K	L	F/n.s.	n.s.	0/2	P	C/S	n.a.	n.a.	15	[217]
Southewest Jiaotong Uni.*(P)	2018	LB	HKA	C	R/An	n.s.	2/10	A	C/HA	pHRI	Position	45	[218]
REUESA(P)	2018	UB	WES	LS	R/An	n.s.	n.s./n.s.	H	n.s./EM	n.a.	n.a.	11.3	[219]
Arizona State Uni.*(P)	2018	UB	E	L	F/n.s.	n.s.	2/0	A	C/PA	pHRI	n.a.	2.5	[220]
NTU (b)*(P)	2018	UB	ES	L	F/n.s.	10	4/1	A	C/EM	cHRI	Voice	20	[122]
Chemnitz Uni. of Tech.*(P)	2018	UB	E	L	F/n.s.	0.5	0/2	A	C/PA	pHRI	Motion	5	[94]
Daiya Industry Co. Ltd*(P)	2018	FB	TH	L	F/n.s.	n.s.	n.a./n.a.	H	C/PM	cHRI	Muscle Act.	n.s.	[221]
Waseda Uni.*(P)	2018	FB	Full Body	C	F/n.s.	n.s.	0/n.a.	P	C/EB	n.a.	n.a.	10	[222]
Pontifical Xavierian Uni.*(P)	2019	UB	ES	L	R/An	n.s.	2/0	A	R/LA	cHRI	Muscle Act.	3	[223]
Aalborg Uni.*(P)	2019	UB	ES	C	R/An	n.s.	6/2	A	R/EM	pHRI	FMG	5	[224]
Hebei Uni. of Tech. (a)*(P)	2019	UB	TH	LC	R/An	n.s.	0/n.s.	P	C/S	n.a.	n.a.	9.5	[225]
Colombia(P)	2019	UB	ES	LC	R/An	n.s.	3/0	A	R/EM	pHRI	Position	n.s.	[72]
e.z.UP®(P)	2019	FB	ESTHK	LCS	F/n.s.	0.75	0/8	P	C/EB	n.a.	n.a.	10	[226]
FLX/V22(P)	2019	UB	T	L	R/An	1.08	0/n.a.	P	R/B	n.a.	n.a.	18.1	[227]
SIAT, Shenzhen*(P)	2019	UB	TH	L	R/An	n.s.	2/n.a.	A	R/EM	pHRI	Motion	25	[228], [229]
H-VEX(Cm)	2019	UB	ST	S	R/Q-An	2.5	0/2	P	C/S	n.a.	n.a.	3	[93], [230]
STIIMA*(-)	2019	UB	ES	LC	R/An	12	2/0	P	C/SEA-PEA	pHRI	Motion	10	[81], [123]
LAD(P)	2019	UB	TH	L	R/An	n.s.	3/2	H	C/SEA-PEA	pHRI	Motion	20	[231]
Chuo Uni. (h)*(P)	2019	LB	K	LC	R/N-An	1.3	0/1	P	C/EB	n.a.	n.a.	15.5	[232]
Uni. of Malaya*(P)	2019	LB	HKA	LC	R/An	11	2/0	A	R/EM	pHRI	Position	4.3	[99]
LWA(P)	2019	UB	TH	L	R/An	n.s.	0/1	P	C/S	n.a.	n.a.	25	[233]
MeBot-EXO(Cm)	2019	Com	H	L	R/An	2.5	0/1	P	C/B	n.a.	n.a.	n.s.	[234], [235]
Hanyang Uni. (c)*(P)	2019	LB	K	C	R/Q-An	n.s.	n.a./2	Q-P	C/S	n.a.	n.a.	20	[236]
Harvard Uni. (g)*(P)	2019	LB	HK	C	F/n.s.	5.4	n.a./0	A	C/EM	pHRI	Position	20.4	[78], [237]
Harbin Inst. of Tech. (d)*(P)	2019	UB	WES	LS	R/N-An	12	3/0	A	R/EM	pHRI	Position	20	[238]
Xi'an Jiaotong Uni.(P)	2019	UB	ST	S	R/N-An	2	0/1	P	C/S	n.a.	n.a.	n.s.	[239]

TABLE 2. *(Continued.)* Exoskeleton classification from 2010 to 2022.

Name (Research Stage[a])	Year	Body Part		Application	Mechanical Design			Powering Method		Control		Testing	Reference
		Type[b]	Assist. Location[c]	Work Type[d]	Structure[e]	Weight[f]	DoF[g]	Drive[h]	Actuator[i]	Strategy[j]	Main Input	Payload	
KAIST (c)*(P)	2019	UB	TH	L	R/An	7.6	0/1	P	R/PA	n.a.	n.a.	15	[240]
ADD, South Korea (a)*(P)	2019	LB	HKA	C	R/An	n.s.	2/5	A	C/EM	pHRI	Position	50	[241]
Georgia Tech*(P)	2019	UB	HK	L	R/An	7	1/1	A	R/EM	pHRI	Position	n.s.	[242]
Uni. of Wyoming (b)*(P)	2019	UB	T	L	R/An	n.s.	0/n.a.	P	n.s./n.s.	n.a.	n.a.	4.5	[243]
SIAT waist(P)	2019	UB	TH	L	R/An	5	1/0	A	C/EM	pHRI	Position	25	[244]
Helmut Schmidt Uni.*(P)	2019	UB	TH	L	F/n.s.	2.4	0/1	P	C/S	n.a.	n.a.	5	[245]
SPEXOR(-)	2019	Com	TH	LS	R/N-An	6.7	n.a./2	P	C/B	n.a.	n.a.	10	[165], [199], [246], [247]
City College of New York*(P)	2019	UB	T	L	F/n.s.	n.s.	0/n.a.	P	C/EB	n.a.	n.a.	15	[248]
STWR(P)	2019	UB	EST	L	F/n.s.	0.96	0/n.a.	P	C/SMA	n.a.	n.a.	4	[249]
Politecnico di Torino (a)*(-)	2019	Com	TH	L	R/An	2.5	n.s./n.s.	n.s.	n.s./n.s.	n.s.	n.s.	15	[250], [251]
Hebei Uni. of Tech. (b)*(-)	2019	LB	HKA	C	R/An	n.s.	0/2	P	C/S	n.a.	n.a.	n.s.	[100]
CEA-List (a)*(P)	2019	UB	ES	L	R/An	n.s.	2/0	A	R/EM	pHRI	Position	n.s.	[252]
UTRCEXO(P)	2019	LB	HKA	C	R/An	21.5	3/0	A	R/EM	pHRI	Position	140	[253]
VT-Lowes(Cm)	2019	UB	TH	L	F/n.s.	n.s.	0/1	P	C/EB	n.a.	n.a.	25	[254]
Av. IPN 2508*(P)	2019	LB	HKA	L	R/An	n.s.	3/0	A	C/PA	pHRI	Position	34	[255]
WPAD(P)	2019	UB	TH	L	R/An	2.5	1/0	A	C/PA	pHRI	Position	10	[256]
XRL(P)	2019	UB	HKA	LC	R/N-An	n.s.	n.a./0	A	R/EM	pHRI	Position	57.12	[257]
Angel-suit(Cm)	2020	LB	HKA	L	R/An	12	4/n.s.	A	C/SEA-PEA	pHRI	Position	0	[258]
UPM (a)*(-)	2020	UB	SE	L	F/n.s.	n.s.	0/4	A	R/EA	pHRI	Position	20	[259]
HipExo(P)	2020	UB	TH	L	R/An	n.s.	1/0	A	C/SEA-PEA	pHRI	Position	15	[115]
H-WEXv2(P)	2020	Com	TH	L	R/An	5.5	2/4	A	C/EM	pHRI	Position	n.s.	[260]
KAIST (a)*(P)	2020	Com	TH	L	R/An	10.5	2/0	A	C/PA	pHRI	Position	9.2	[63]
Chuo Uni. (b)*(P)	2020	LB	K	L	R/N-An	n.s.	n.a./2	P	C/S	pHRI	n.a.	15.5	[133]
legX(Cm)	2020	LB	K	S	F/N-An	2.5	1/0	P	C/S	n.a.	n.a.	n.s.	[261]
Berlin Uni.of the Arts*(P)	2020	FB	WEST	LS	F/n.s.	n.s.	n.a./n.a.	A	C/PM	pHRI	n.s.	n.s.	[262]
Uni. of Wyoming (a)*(P)	2020	UB	T	L	F/Q-An	2.5	0/>20	P	C/S	n.a.	n.a.	n.s.	[263]
SIAT-WEXV2(-)	2020	UB	T	L	R/Q-An	4.98	1/2	A	C/SEA-PEA	pHRI	Position	25	[264]
Uni. of Michigan*(P)	2020	LB	K	L	F/N-An	n.s.	n.a./1	P	C/SMA	n.a.	n.a.	n.s.	[134]
Heidelberg Uni.*(-)	2020	UB	EST	L	F/An	n.s.	n.a/0	A	C/EM	pHRI	Position	2	[265]
NTU (a)*(P)	2020	UB	E	L	F/Q-An	7.5	4/0	A	R/EM	pHRI	Voice	n.s.	[96]
WALV(P)	2020	UB	T	L	F/N-An	n.s.	0/n.s.	P	C/S	n.a.	n.a.	n.s.	[266]
XoTrunk(-)	2020	LB	T	LCS	R/N-An	6	1/0	A	R/EM	pHRI	Pressure	15	[267], [268]
Panto-Arm Exo(P)	2020	UB	ES	S	R/N-An	n.s.	1/0	H	C/EM	pHRI	Pressure	60	[269]
NEU, Shenyang (a)*(P)	2020	UB	ES	LCS	R/An	5.6	6/2	A	C/PM	pHRI	Pressure	6	[270]
CEA-List (b)*(P)	2020	UB	ES	LC	R/An	n.s.	4/0	A	n.s./n.s.	cHRI	Muscle Act.	5	[271]
UESTC*(P)	2020	UB	ES	L	R/An	2.78	4/0	A	R/EM	pHRI	Motion	30	[272]

TABLE 2. *(Continued.)* **Exoskeleton classification from 2010 to 2022.**

Name (Research Stage[a])	Year	Body Part		Application	Mechanical Design			Powering Method		Control		Testing	Reference
		Type[b]	Assist. Location[c]	Work Type[d]	Structure[e]	Weight[f]	DoF[g]	Drive[h]	Actuator[i]	Strategy[j]	Main Input	Payload	
KAIST (d)*(P)	2020	Com	H	L	F/An	6	2/0	A	C/EM	pHRI	Motion	10	[97]
Akita Prefectural Uni.*(P)	2020	UB	E	L	R/An	n.s.	1/0	A	C/PM	pHRI	Muscle Act.	2.5	[273]
ELE-ROBOT(P)	2020	Com	THK	C	R/An	17	4/0	A	R/HA	pHRI	Position	35	[274]
Miguel Hernández Uni.*(P)	2020	UB	ES	LS	R/Q-An	n.s.	4/0	A	R/EM	pHRI	Motion	1.7	[275]
Hebei Uni. of Tech. (c)*(P)	2020	Com	T	L	R/N-An	n.s.	0/3	P	C/S	n.a.	n.a.	10	[276]
ShoulderX(Cm)	2020	UB	S	S	F/N-An	n.s.	0/2	H	n.s/n.s	n.a.	n.a.	n.s.	[277]
MWWAR(P)	2020	UB	TH	LS	R/An	2.5	1/0	A	C/PM	pHRI	Position	35	[278]
Muscle Suit Every (Cm)	2022	Com	TH	LC	R/N-An	4.4	n.a./1	P	C/EB	n.a.	n.a.	25.5	[279]
ES-RSEA(P)	2022	LB	H	L	R/An	n.s.	1/0	A	C/SEA-PEA	n.s.	n.s.	25	[280]
ABX(P)	2022	Com	TH	L	F/N-An	6.4	3/0	A	R/EM	pHRI	Motion	22.7	[281]
Exo4Work(P)	2022	Com	ST	LS	R/Q-An	4.14	0/6	P	C/S	n.a.	n.a.	10	[282]
ArmX(P)	2022	UB	ES	L	R/Q-An	7	6/8	H	R/EM	pHRI	Position	5	[283]
E-Leg(P)	2022	LB	KA	S	R/An	3	1/1	H	R/EM	pHRI	Motion	n.a.	[284]

[a] Name (Research Stage): If the name of the device is specified in the literature, it is shown in the cell. If the name is not specified , the name of first author's university is shown and marked with ∗ (if same university is appearing multiple times, its presented as (a), (b), (c) etc.). / C - Concept, P - Prototype, Com - Commercial;
[b] Type [Body Part]; LB - Lower Body, UB - Upper body, FB - Full body, Com - Combination;
[c] Assisting Location [Body Part]: W - Wrist, E - Elbow, S - Shoulder, T - Trunk, H - Hip, K - Knee, A - Ankle, F - Foot;
[d] Work Type [Application]: L - Lifting, C - Carrying, S - Static holding;
[e] Structure [Mechanical Design]: R - Rigid, C - Compliant / An - Anthropomorphic, Q-An - Quasi-Anthropomorphic, N-An - Non-Anthropomorphic;
[f] Weight [Mechanical Design]: kg;
[g] Degrees of Freedom [Mechanical Design]: Active DoF / Passive DoF;
[h] Drive [Powering Method]: A - Active, P - Passive, H - Hybrid, Q-P - Quasi-passive, P-Bp - Passive (body powered);
[i] Actuator [Powering Method]: R - Rigid, C - Compliant / Electric Motors - EM, Pneumatic Actuators - PA, Hydraulic Actuators - HA, Pneumatic Muscle - PM, Shape Memory Alloy - SMA, SEAs/PEAs - Series/Parallel Elastic Actuators, Springs - S, Gas Springs - GS, Beams - B, Elastic Bands - EB;
[j] Strategy [Control]: pHRI - Physical Human Robot Interaction, cHRI - Cognitive Human Robot Interaction;
[*] n.s. - Not Specified (For the values/categories which are not specified in literature), n.a. - Not Applicable (For the values/categories which are not applicable for the device);

TABLE 3. Most frequent keywords (2010-2022).

Author Keywords	Articles
Exoskeleton + Exoskeletons	60+13
Wearable Robot + Wearable Robots	13+10
Electromyography + EMG	19+9
Low Back Pain + Low-Back Pain	8+6
Lifting	9
Wearable	9
Assistive Device	8
Biomechanics	8
Ergonomics	7
Muscle Activity	7

increased from 2 to 40 within a span of 12 years (see Fig. 11) with an annual growth rate of 31.4%. Exponential fitting of the data revealed a growth of the research area ($r^2 = 0.94$).

A co-word analysis draws the conceptual structure of a framework using a word co-occurrence network to map and cluster terms extracted from keywords, titles, or abstracts in a bibliographic collection. Figure 12 shows the evolution of the most significant keywords using visual representations of keyword co-occurrence networks.

VI. DISCUSSION AND FUTURE DIRECTIONS

The review of the literature presented in the previous section provides a comprehensive overview of the manual handling exoskeletons developed in the last 12 years. Analysing this data, the authors have identified the challenges, trends, and future directions of this research field in the following subsections.

A. CHALLENGES IN DEVELOPING THE MANUAL HANDLING EXOSKELETONS

Designing exoskeletons for manual handling has several design challenges compared to exoskeletons designed for rehabilitative and assistive purposes. The users of the manual handling exoskeletons are considered to be unimpaired in their motor capacity. This means that the exoskeleton should be designed to support a wide variety of natural movements. Therefore, when compared with assistive or rehabilitative exoskeletons, higher compliance is required for the manual handling exoskeletons to accommodate such varying movements made by the users.

One observation made by the authors is that in most lower body and trunk support devices with hip joint assistance, the DoFs of the hip are compromised. Since the hip joint is a spherical joint, the exoskeleton should be designed to support (actively/passively) three DOFs in FL/EX, AB/AD, and IR/ER. If the exoskeleton's DOFs are constrained in the transverse plane and the frontal plane, the wearer's natural motions occurring during manual handling work could be affected and would increase the risk of WMSDs. Another commonly compromised DOF that can be seen in the lower body exoskeletons is the IN/EV of the ankle joint. In most systems, the focus has been on the DF/PF movements of the ankle. Thus the effect of the mechanical systems on the IN/EV movement is often overlooked. The inhibition of this DOF can lead the wearer to deviate from the natural gait pattern and cause cumulative trauma injuries.

The implications of such constrained movements might not be significant if the pre-defined, text-book lifting, load-carrying, or static holding poses are considered. But in reality, the users work in a dynamic environment where the movements constrained to a single plane might not be possible. Specifically, in cases such as handling asymmetric loads (e.g. healthcare practitioners handling bed-ridden patients), a combination of movements such as ''lift-turn-place'' (e.g. industrial workers in a production line), and standing/walking in uneven terrain (e.g. military personnel walking in rough terrains in their line of duty), it is very important to have high compliance in the exoskeletons. So far, addressing these practical issues has been a challenging aspect of the design of manual handling exoskeletons.

Static holding is the most common use for upper body power augmentation exoskeletons. The design concerns for these exoskeletons include the need to address the high bending moments and forces applied to the linkage system in mechanisms. As a result, the mechanical designs of most of these devices tend to be bulky and non-anthropomorphic. These design limitations can limit the ranges of motion of the wearer and prevent the ability to navigate or manoeuvre in tight workspaces. Avoiding this issue of heavy and bulky designs in developing upper body exoskeletons has been another challenging aspect that the authors observed.

The weight-to-assist ratio is an important factor that should be considered in developing manual handling exoskeletons. Since the exoskeletons are developed to provide additional assistance for the wearers, these should not increase the loads experienced by the users. While many lower extremity exoskeletons are capable of directly grounding the load through the linkages, it is inevitable that upper body exoskeletons exert an additional load on the wearer in terms of the added weight of the device. There have been attempts to reduce this issue by utilising flexible structures in place of rigid ones, in the hope of reducing the weight of the device. However, in doing so, the assistance that can be provided by the exoskeleton is often compromised. Therefore, this issue of achieving an optimal weight-to-assist ratio remains a challenging aspect of the design of manual handling exoskeletons.

Exoskeletons are typically designed for specific anthropometry such as the 50th percentile male population. Since the range of wearers can have different body segment variations to that of the anthropometric data in the literature, the designs should have specific features to compensate for joint axis misalignments. In addition to that, anthropometric variations of the users may implicate differences in the loads acting on the exoskeleton. Thus it is important to provide the wearer with the ability to control the assistive torque on the joints whenever required. Such flexibility in the structure and the control may result in complex exoskeletons. Therefore,

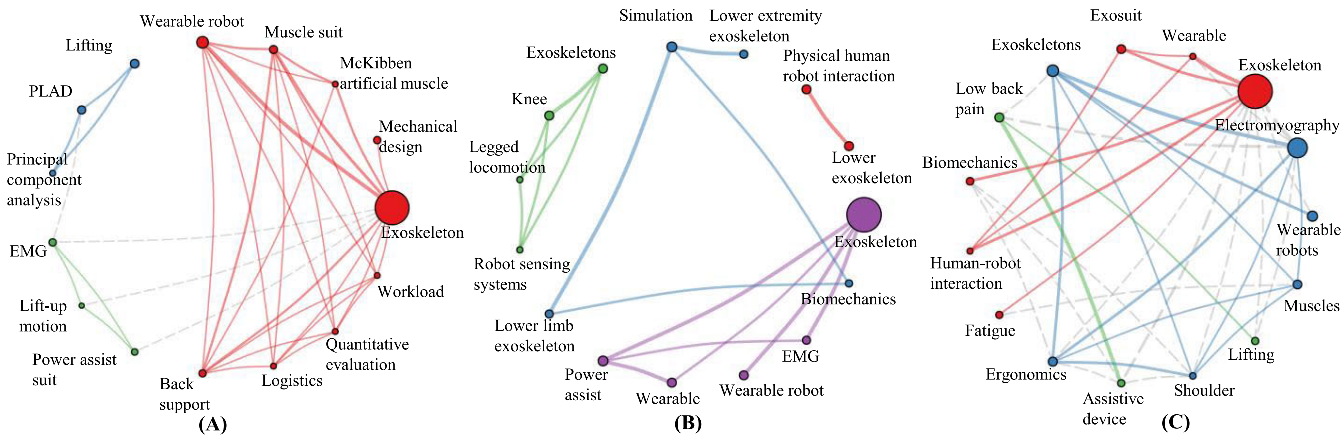

FIGURE 12. Author keyword co-occurrence network (KCN) visual representations for three time periods along with most significant 20 keywords; (A) KCN for 2010-2014, (B) KCN for 2015-2017, (C) KCN for 2018-2022.

it remains a challenge in current devices to achieve high compatibility with the user.

B. RESEARCH TRENDS AND FUTURE DIRECTIONS

According to the bibliometric analysis, in the past decade, an exponential growth of annual publications related to the manual handling of exoskeletons can be seen. This is a highly favourable trend, which can be an indication of several factors. The technological advancements can have both direct and indirect impacts on this trend.

The research advancements on lighter and stronger materials have opened novel possibilities to achieve a lower weight-to-assist ratio, thus encouraging researchers to utilise such material in their designs. The advancements in the field of cognitive human-robot interactions have encouraged the use of bio-signal-based actuation, thus providing an incentive to perform more research on manual handling exoskeletons. The invention of soft robotic actuators such as pneumatic muscle has also impacted the increased interest in this research area.

The technological advancements have also had an indirect effect on the development of manual handling exoskeletons. Specifically, with the increased production in industrial settings, the manual handling workload of the industrial workers has increased. This, along with the increased considerations on the safety of the employees adopted by the industries has increased the requirement of proper manual handling exoskeletons to avoid WMSD. Therefore, the exponential growth of the related research publications can be expected.

The keyword co-occurrence networks in Fig. 12 provide valuable information about the change in the focus of the research work during the last decade. When considering the body part of interest, it can be seen that during the period of 2010-2014, the focus has been on back-support exoskeletons. However, by the period 2015-2017, an increased interest towards developing lower extremity exoskeletons, specifically the devices developed to support the knee joint can be seen. But in the latter part of the last decade, the frequent mentions of ''low-back pain'' and ''shoulder'' in the keywords suggest that there is a trend towards the development of exoskeletons for the upper body.

These keyword co-occurrence networks also reveal that during the latter part of the last decade, there has been a rise of occurring ''electromyography'' as a keyword. This suggests that there is a trend to use EMG technology in the latest manual handling exoskeletons.

In the review, the authors observed a trend towards developing the exoskeletons for lifting. Out of the manual handling tasks, lifting is considered the most commonly encountered issue, specifically in an industrial setting. Inherently, the workers have to engage in load-lifting tasks and even if the loads are low to moderate, prolonged repetitive tasks might cause WMSD. Therefore, it can be expected to have a higher publication output focusing on lift-support exoskeletons.

An interesting tendency in the mechanical design of manual handling exoskeletons is the use of flexible components. Especially in trunk exoskeletons, the tendency to use flexible structures and passive actuation methods has been apparent. This can be a result of the low weight-to-assist ratio provided by the flexible structures. Furthermore, the lower body exoskeletons also show an increasing trend towards using passive actuation methods. However, in upper-body exoskeletons, the inclusion of soft or flexible structures was rarely noticed. Even though research on soft exoskeletons is considered a hot topic in recent times, the feasibility of adopting this technology in the upper body exoskeletons is still questionable since flexible structures often provide low assistance when compared with rigid structures while the upper body exoskeletons demand high assistive forces.

Another significant trend in the manual handling exoskeletons is to develop mechanisms with higher degrees of freedom. Although earlier designs seemed to be focused on supporting only some of the degrees of freedom in the human joints, the recent research work is focused on providing maximum mobility to the wearers. Therefore, more emphasis on developing devices with complete degrees of freedom can be seen as a trend in these exoskeletons.

The analysis of the powering mechanisms mentioned in the selected literature shows that many devices are active devices. This shows that the trend to develop ''robotic'' exoskeletons has increased during the last decade. With the advancements in robotic technologies, this is to be expected. Another reason for the increased interest towards developing robotic devices might be the versatility of the control strategies. In the actively powered exoskeletons, the most commonly encountered actuation method is the electric motor. However, there is a trend to combine the electric motors with passive components to achieve more compliance as in series elastic actuators. In active exoskeletons which have not used electric motors, the pneumatic muscle was a common occurrence. The similarity in the actuation kinematics of the pneumatic muscle to actual human muscle actuation might have played a role in encouraging this actuation method. However, the use of pneumatically powered systems tends to add additional bulky components to the exoskeletons ultimately increasing its weight.

When the control strategies in the manual handling exoskeletons are considered, one important feature is that the physical human-robot interaction takes a more prominent place rather than the cognitive human-robot interactions. Although a considerable number of devices have utilised cognitive human-robot interactions during the early years of the last decade, these occurrences have gradually decreased in the latter years. While cognitive human-robot interactions such as the use of EMG or EEG for human motion intention detection are sophisticated technologies, there can be several reasons for opting out of cognitive human-robot interactions. One major concern is the portability of the devices. Unlike rehabilitation devices, manual handling exoskeletons are to be used in an occupational environment where the users might be involved in walking and other activities. In such cases, having cognitive human-robot interaction interfaces will be problematic, especially since many such interfaces come with multiple electrodes and systems with high processing power. Additionally, when using bio-signals for detecting the human motion intention, a high noise can be expected which would require training of the user as well as the control system prior to the use by each user. Due to these factors, a trend towards physical human-robot interactions can be seen, where the signals have less noise and the systems have better portability.

In recent research studies, heightened attention to evaluating the effectiveness of the exoskeletons was noted. This has led to the development of extensive methodological approaches for testing and experimenting. However, studies on the feasibility of exoskeletons in work environments have been overlooked in the current research. However, with the trends of improved evaluation methods, the authors expect that this will be addressed in the future more significantly.

When considering the overall trends, it can be seen that the manual handling exoskeletons are improved mainly in two aspects, namely performance and comfort. In the sense of performance, the ability of the exoskeletons to support the load has improved. On the other hand, in the view of enhancing user compatibility, the weight of the exoskeletons is being reduced and the flexibility to perform natural movements is being improved. In essence, these requirements have led exoskeletons to be developed with complex structures and light materials.

There are several deficiencies that the authors have identified in the currently available manual handling exoskeletons.

Despite the trend to support more DOFs, only a limited number of researchers have attempted to map all three DoFs of the hip joint. Furthermore, some have restricted the motion of internal, and external rotation due to a lower range of motion during manual handling. Although restriction of internal/external rotation helps to simplify the design process, this approach also hinders the natural motion of the human body. A similar tendency can be seen in the back support exoskeletons where the lateral bending and twisting motions of the spine are disregarded in most designs. Stiffness in the lower back region and flexibility in the spine are not considered in most of the exoskeletons developed for load lifting. The exoskeleton's compliance with the back has been compromised as a result of the added stiffness and inclusion of complex mechanisms. However, as mentioned under the challenges, these will affect the mobility of the user and restrict the types of movements that they can carry out. The human workers who are the target users for these devices have different biomechanics and unlike the robot workers, it cannot be expected from the human workers to always move in a predefined manner. It will not only be unrealistic but also will reduce the working efficiency significantly. However, with the current trends to develop more biomechanically compatible devices, it is hoped that future exoskeletons will provide better flexibility and mobility, encouraging more industries to use such exoskeletons for the health and safety of their employees.

Another significant gap identified by the authors was the lack of research on passive energy harvesting in load-lifting exoskeletons. A few exoskeletons have attempted to recover passive energy during load lifting, though some have used parallel springs to harness energy without taking into account the available passive energy. However, given that one of the most common issues in manual handling exoskeletons is increased weight due to high power requirements, it is worthwhile to look into the possibility of incorporating energy harvesting methods into these devices. The authors anticipate that this will be taken into account more in future designs.

Some research papers on occupational exoskeletons failed to report the evaluation methods and results when investigating the performance evaluation aspect of the devices. Muscle activity has been used as a performance indicator in many papers that have this information. The choice of muscle groups, on the other hand, varies, making it difficult to compare the performance of similar devices. Furthermore, despite the importance of human-robot interaction, most robotic devices lacked performance evaluation. Furthermore, obtaining an accurate assessment of these devices has been difficult due to a lack of information about field testing of the developed devices. As a result, the authors identified the need for a proper evaluation guideline for load handling occupational exoskeletons. This would facilitate the process of benchmarking non-commercial devices. A proper benchmarking system will encourage researchers to thoroughly test the developed devices and will provide specific data on the performance of these exoskeletons. Such data could help to accelerate research by highlighting research gaps.

According to the findings of this review, the field of manual handling exoskeletons is on a positive research trajectory. These devices have evolved from earlier designs of exoskeletons with limited resources and primitive technologies to become more sophisticated devices. With constant technological advancements occurring in peripheral fields such as materials, actuator developments, sensing, and control strategies, manual handling exoskeleton designs still have a long way to go. Although many devices are still restricted to specific tasks and motions, trends are pointing toward the development of more versatile devices with greater degrees of freedom. It is hoped that advances in technology will accelerate these advancements, making augmented super-human workers with the strength of machines and the cognition and dexterity of humans a reality one day.

REFERENCES

[1] A. Luttman and G. Caffier, ''Preventing musculoskeletal disorders in the workplace,'' World Health Org., Geneva, Switzerland, Tech. Rep., 2003.

[2] *Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back. U.S. Department of Health and Human Services, Public Health Service, Centers F*, National Institute for Occupational Safety and Health, Washington, DC, USA, 1997, pp. 1–590.

[3] *GBD Compare: IHME Viz Hub*, Univ. Washington, Washington, DC, USA, 2020.

[4] P. Yuan, T. Wang, F. Ma, and M. Gong, ''Key technologies and prospects of individual combat exoskeleton,'' in *Knowledge Engineering and Management, Advances in Intelligent Systems and Computing*, vol. 214, F. Sun, Eds. Berlin, Germany: Springer, 2014, pp. 305–316.

[5] P. Graham and J. P. Dougherty, ''Oh, their aching backs!: Occupational injuries in nursing assistants,'' *Orthopaedic Nursing*, vol. 31, no. 4, pp. 218–223, 2012.

[6] B. R. da Costa and E. R. Vieira, ''Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies,'' *Amer. J. Ind. Med.*, vol. 53, no. 3, pp. 285–323, Mar. 2009.

[7] J. Marcum and D. Adams, ''Work-related musculoskeletal disorder surveillance using the Washington state workers' compensation system: Recent declines and patterns by industry, 1999–2013,'' *Amer. J. Ind. Med.*, vol. 60, no. 5, pp. 457–471, May 2017.

[8] A. M. Dollar and H. Herr, ''Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art,'' *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 144–158, Feb. 2008.

[9] M. Vukobratovic, D. Hristic, and Z. Stojiljkovic, ''Development of active anthropomorphic exoskeletons,'' *Med. Biol. Eng.*, vol. 12, no. 1, pp. 66–80, Jan. 1974.

[10] H. Kazerooni, ''Extenders: Human machine interaction via the transfer of power and information signals,'' in *Proc. IEEE Int. Workshop Intell. Robots*, Oct. 1988, pp. 737–742.

[11] H. Kazerooni, ''Exoskeletons for human power augmentation,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2005, pp. 3459–3464.

[12] Y. Sankai, ''Leading edge of cybernics: Robot suit HAL,'' in *Proc. SICE-ICASE Int. Joint Conf.*, Oct. 2006, p. 1.

[13] S. J. Zaroodny, ''Bumpusher—A powered aid to locomotion,'' Ballistic Research Labs Aberdeen Proving Ground MD, Adelphi, MD, USA, Tech. Rep. AD0632139, 1963.

[14] R. S. Mosher, ''Handyman to Hardiman,'' General Electr. Company, Boston, MA, USA, Tech. Rep. 670088, 1967.

[15] B. R. Fick and J. B. Makinson, ''Final report on hardiman I prototype for machine augmentation of human strength and endurance,'' General Electr. Company, Boston, MA, USA, Tech. Rep. 196, 1971.

[16] M. K. Vukobratovic, ''When were active exoskeletons actually born?'' *Int. J. Humanoid Robot.*, vol. 4, no. 3, pp. 459–486, Sep. 2007.

[17] J. A. Moore, *Pitman a Powered Exoskeleton Suit for the Infantryman*, vol. 16. Los Alamos, NM, USA: Los Alamos National Laboratory, 1986.

[18] M. E. Rosheim, ''Man-amplifying exoskeleton,'' in *Mobile Robots IV*, vol. 1195. Bellingham, WA, USA: SPIE, 1990, pp. 402–411.

[19] H. Kazerooni, ''The Berkeley lower extremity exoskeleton,'' in *Tracts in Advanced Robotics*, vol. 25. Cham, Switzerland: Springer, 2006, pp. 9–15.

[20] E. Guizzo and H. Goldstein, ''The rise of the body bots [robotic exoskeletons,'' *IEEE Spectr.*, vol. 42, no. 10, pp. 50–56, Oct. 2005.

[21] C. J. Walsh, K. Endo, and H. Herr, ''A quasi-passive leg exoskeleton for load-carrying augmentation,'' *Int. J. Humanoid Robot.*, vol. 4, no. 3, pp. 487–506, Sep. 2007.

[22] M. Ishii, K. Yamamoto, and K. Hyodo, ''Stand alone wearable power assisting suit (development and availability),'' *Trans. Jpn. Soc. Mech. Eng. Ser. C*, vol. 72, no. 715, pp. 857–864, 2006.

[23] H. Kazerooni, ''A review of the exoskeleton and human augmentation technology,'' in *Proc. ASME Dyn. Syst. Control Conf., A B*, Jan. 2008, pp. 1539–1547.

[24] C.-J. Yang, J.-F. Zhang, Y. Chen, Y.-M. Dong, and Y. Zhang, ''A review of exoskeleton-type systems and their key technologies,'' *Proc. Inst. Mech. Eng., C, J. Mech. Eng. Sci.*, vol. 222, no. 8, pp. 1599–1612, Aug. 2008.

[25] R. A. R. C. Gopura, K. Kiguchi, and D. S. V. Bandara, ''A brief review on upper extremity robotic exoskeleton systems,'' in *Proc. 6th Int. Conf. Ind. Inf. Syst.*, Aug. 2011, pp. 346–351.

[26] R. Bogue, ''Robotic exoskeletons: A review of recent progress,'' *Ind. Robot, Int. J.*, vol. 42, no. 1, pp. 5–10, Jan. 2015.

[27] Z. Zhu, A. Dutta, and F. Dai, ''Exoskeletons for manual material handling—A review and implication for construction applications,'' *Autom. Construct.*, vol. 122, Feb. 2021, Art. no. 103493.

[28] T. Yan, M. Cempini, C. M. Oddo, and N. Vitiello, ''Review of assistive strategies in powered lower-limb orthoses and exoskeletons,'' *Robot. Auto. Syst.*, vol. 64, pp. 120–136, Feb. 2015.

[29] B. Chen, H. Ma, L.-Y. Qin, F. Gao, K.-M. Chan, S.-W. Law, L. Qin, and W.-H. Liao, ''Recent developments and challenges of lower extremity exoskeletons,'' *J. Orthopaedic Transl.*, vol. 5, pp. 26–37, Apr. 2016.

[30] H. F. N. Al-Shuka, M. H. Rahman, S. Leonhardt, I. Ciobanu, and M. Berteanu, ''Biomechanics, actuation, and multi-level control strategies of power-augmentation lower extremity exoskeletons: An overview,'' *Int. J. Dyn. Control*, vol. 7, no. 4, pp. 1462–1488, Dec. 2019.

[31] M. Pesenti, A. Antonietti, M. Gandolla, and A. Pedrocchi, ''Towards a functional performance validation standard for industrial low-back exoskeletons: State of the art review,'' *Sensors*, vol. 21, no. 3, p. 808, Jan. 2021.

[32] A. De Vries and M. De Looze, ''The effect of arm support exoskeletons in realistic work activities: A review study,'' *J. Ergon*, vol. 9, no. 4, pp. 1–9, 2019.

[33] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, ''Developments in hardware systems of active upper-limb exoskeleton robots: A review,'' *Robot. Auto. Syst.*, vol. 75, pp. 203–220, Jan. 2016.

[34] T. Kermavnar, A. W. de Vries, M. P. de Looze, and L. W. O'Sullivan, ''Effects of industrial back-support exoskeletons on body loading and user experience: An updated systematic review,'' *Ergonomics*, vol. 64, no. 6, pp. 685–711, Jun. 2021.

[35] S. Toxiri, M. B. Näf, M. Lazzaroni, J. Fernández, M. Sposito, T. Poliero, L. Monica, S. Anastasi, D. G. Caldwell, and J. Ortiz, ''Back-support exoskeletons for occupational use: An overview of technological advances and trends,'' *IISE Trans. Occupational Ergonom. Hum. Factors*, vol. 7, nos. 3–4, pp. 237–249, Oct. 2019.

[36] J. Theurel and K. Desbrosses, "Occupational exoskeletons: Overview of their benefits and limitations in preventing work-related musculoskeletal disorders," *IISE Trans. Occupational Ergonom. Hum. Factors*, vol. 7, nos. 3–4, pp. 264–280, Oct. 2019.

[37] B. Chen, B. Zi, Z. Wang, L. Qin, and W.-H. Liao, "Knee exoskeletons for gait rehabilitation and human performance augmentation: A state-of-the-art," *Mechanism Mach. Theory*, vol. 134, pp. 499–511, Apr. 2019.

[38] B. Chen, B. Zi, L. Qin, and Q. Pan, "State-of-the-art research in robotic hip exoskeletons: A general review," *J. Orthopaedic Transl.*, vol. 20, pp. 4–13, Jan. 2020.

[39] M. P. de Looze, T. Bosch, F. Krause, K. S. Stadler, and L. W. O'Sullivan, "Exoskeletons for industrial application and their potential effects on physical work load," *Ergonomics*, vol. 59, no. 5, pp. 671–681, May 2016.

[40] J. K. Proud, D. T. H. Lai, K. L. Mudie, G. L. Carstairs, D. C. Billing, A. Garofolini, and R. K. Begg, "Exoskeleton application to military manual handling tasks," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 64, no. 3, pp. 527–554, May 2022.

[41] N. Hoffmann, G. Prokop, and R. Weidner, "Methodologies for evaluating exoskeletons with industrial applications," *Ergonomics*, vol. 65, no. 2, pp. 276–295, Feb. 2022.

[42] J. R. Meda-Gutiérrez, L. A. Zúñiga-Avilés, A. H. Vilchis-González, and J. C. Ávila-Vilchis, "Knee exoskeletons design approaches to boost strength capability: A review," *Appl. Sci.*, vol. 11, no. 21, p. 9990, Oct. 2021.

[43] G. Bao, L. Pan, H. Fang, X. Wu, H. Yu, S. Cai, B. Yu, and Y. Wan, "Academic review and perspectives on robotic exoskeletons," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 11, pp. 2294–2304, Nov. 2019.

[44] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J. Bus. Res.*, vol. 133, pp. 285–296, Sep. 2021.

[45] S. J. Hall, *Basic Biomechanics*, 7th ed. New York, NY, USA: McGraw-Hill, 2015.

[46] Z. Wang, L. Wu, J. Sun, L. He, S. Wang, and L. Yang, "Squat, stoop, or semi-squat: A comparative experiment on lifting technique," *J. Huazhong Univ. Sci. Technol. [Med. Sci.]*, vol. 32, no. 4, pp. 630–636, Aug. 2012.

[47] M. Nordin and V. H. Frankel, *Basic Biomechanics of the Musculoskeletal System*, 4th ed. Philadelphia, PA, USA: Lippincott Williams & Wilkins, 2012.

[48] J. H. van Dieën, M. J. M. Hoozemans, and H. M. Toussaint, "Stoop or squat: A review of biomechanical studies on lifting technique," *Clin. Biomech.*, vol. 14, no. 10, pp. 685–696, Dec. 1999.

[49] S. Hwang, Y. Kim, and Y. Kim, "Lower extremity joint kinetics and lumbar curvature during squat and stoop lifting," *BMC Musculoskeletal Disorders*, vol. 10, no. 1, p. 15, Dec. 2009.

[50] R. Martinez, N. Assila, E. Goubault, and M. Begon, "Sex differences in upper limb musculoskeletal biomechanics during a lifting task," *Appl. Ergonom.*, vol. 86, Jul. 2020, Art. no. 103106.

[51] T.-H. Lee, "Muscular activity and acceleration of box vibration in manual holding tasks: Effects of load and height of the load's center of gravity," *Int. J. Occupational Saf. Ergonom.*, vol. 26, no. 1, pp. 15–19, Jan. 2020.

[52] N. Arjmand and A. Shirazi-Adl, "Biomechanics of changes in lumbar posture in static lifting," *Spine*, vol. 30, no. 23, pp. 2637–2648, Dec. 2005.

[53] W.-J. Chen, W.-K. Chiou, Y.-H. Lee, M.-Y. Lee, and M.-L. Chen, "Myo-electric behavior of the trunk muscles during static load holding in healthy subjects and low back pain patients," *Clin. Biomech.*, vol. 13, no. 1, pp. S9–S15, Jan. 1998.

[54] M. A. Holbein and M. S. Redfern, "Postural stability while holding loads in various postures," in *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 37, no. 10. Los Angeles, CA, USA: SAGE, 1993, pp. 697–700.

[55] P. K. Nag, "Endurance limits in different modes of load holding," *Appl. Ergonom.*, vol. 22, no. 3, pp. 185–188, Jun. 1991.

[56] J. F. Seay, "Biomechanics of load carriage—Historical perspectives and recent insights," *J. Strength Conditioning Res.*, vol. 29, no. 11, pp. S129–S133, Nov. 2015.

[57] S. A. Birrell and R. A. Haslam, "The effect of military load carriage on 3-D lower limb kinematics and spatiotemporal parameters," *Ergonomics*, vol. 52, no. 10, pp. 1298–1304, Oct. 2009.

[58] K. Schaub, *Ergonomics—Manual Handling—Part 1: Lifting and Carrying*, International Organization for Standardization, Geneva, Switzerland, May 2003.

[59] T. R. Waters, V. Putz-Anderson, A. Garg, and L. J. Fine, "Revised NIOSH equation for the design and evaluation of manual lifting tasks," *Ergonomics*, vol. 36, no. 7, pp. 749–776, Jul. 1993.

[60] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *PLoS Med.*, vol. 6, pp. 1–6, Jul. 2009.

[61] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *Brit. Med. J.*, vol. 372, pp. 1–12, Apr. 2021.

[62] H. Lee, W. Kim, J. Han, and C. Han, "The technical trend of the exoskeleton robot system for human power assistance," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 8, pp. 1491–1497, Aug. 2012.

[63] U. Heo, S. J. Kim, and J. Kim, "Backdrivable and fully-portable pneumatic back support exoskeleton for lifting assistance," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 2047–2053, Apr. 2020.

[64] J. Theurel, K. Desbrosses, T. Roux, and A. Savescu, "Physiological consequences of using an upper limb exoskeleton during manual handling tasks," *Appl. Ergonom.*, vol. 67, pp. 211–217, Feb. 2018.

[65] Y. Muramatsu, H. Umehara, and H. Kobayashi, "Improvement and quantitative performance estimation of the back support muscle suit," in *Proc. 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2013, pp. 2844–2849.

[66] H. Heydari, M. Hoviattalab, M. R. Azghani, M. Ramezanzadehkoldeh, and M. Parnianpour, "Investigation on a developed wearable assistive device (WAD) in reduction lumbar muscles activity," *Biomed. Eng., Appl., Basis Commun.*, vol. 25, no. 3, May 2013, Art. no. 1350035.

[67] K. Kashiwagi, T. Nakakuki, and C. Ishii, "Discrimination of Waist motions based on surface EMG for Waist power assist suit using support vector machine," in *Proc. 50th IEEE Conf. Decis. Control Eur. Control Conf.*, Dec. 2011, pp. 3204–3209.

[68] M. Tsuzura, T. Nakakuki, and D. Misaki, "A mechanism design of Waist power assist suit for a caregiver by using torsion springs," in *Proc. 13th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2013, pp. 866–868.

[69] C. Ste-Croix, D. Tack, D. Boucher, F. Ruel, G. Pageau, and S. Bedard, "Experimental evaluation of the dermoskeleton concept: Addressing the soldiers overload challenge," in *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 56, no. 1, Sep. 2012, pp. 2393–2396.

[70] L. M. Mooney, E. J. Rouse, and H. M. Herr, "Autonomous exoskeleton reduces metabolic cost of human walking during load carriage," *J. NeuroEng. Rehabil.*, vol. 11, no. 1, p. 80, Dec. 2014.

[71] W. van Dijk, T. Van de Wijdeven, M. M. Holscher, R. Barents, R. Könemann, F. Krause, and C. L. Koerhuis, "Exobuddy–A non-anthropomorphic quasi-passive exoskeleton for load carrying assistance," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 336–341.

[72] S. López-Méndez, H. V. Martínez-Tejada, and M. F. Valencia-García, "Development of an armored upper limb exoskeleton," *Revista Facultad de Ingeniería Universidad de Antioquia*, vol. 95, pp. 109–117, Dec. 2019.

[73] R. Altenburger, D. Scherly, and K. S. Stadler, "Design of a passive, ISO-elastic upper limb exoskeleton for gravity compensation," *ROBOMECH J.*, vol. 3, no. 1, pp. 1–7, Apr. 2016.

[74] K. Huysamen, M. de Looze, T. Bosch, J. Ortiz, S. Toxiri, and L. W. O'Sullivan, "Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks," *Appl. Ergonom.*, vol. 68, pp. 125–131, Apr. 2018.

[75] S. Toxiri, A. Calanca, J. Ortiz, P. Fiorini, and D. G. Caldwell, "A parallel-elastic actuator for a torque-controlled back-support exoskeleton," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 492–499, Jan. 2018.

[76] A. S. Koopman, I. Kingma, G. S. Faber, M. P. de Looze, and J. H. van Dieën, "Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks," *J. Biomech.*, vol. 83, pp. 97–103, Jan. 2019.

[77] S.-H. Hyon, T. Hayashi, A. Yagi, T. Noda, and J. Morimoto, "Design of hybrid drive exoskeleton robot XoR_2," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 4642–4648.

[78] T. Schmalz, J. Schändlinger, M. Schuler, J. Bornmann, B. Schirrmeister, A. Kannenberg, and M. Ernst, "Biomechanical and metabolic effectiveness of an industrial exoskeleton for overhead work," *Int. J. Environ. Res. Public Health*, vol. 16, no. 23, p. 4792, Nov. 2019.

[79] Z. Luo and Y. Yu, "Wearable stooping-assist device in reducing risk of low back disorders during stooped work," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2013, pp. 230–236.

[80] I. D. Wijegunawardana, M. B. K. Kumara, H. H. M. J. De Silva, P. K. P. Viduranga, R. K. P. S. Ranaweera, R. A. R. C. Gopura, and D. G. K. Madusanka, "ChairX: A robotic exoskeleton chair for industrial workers," in *Proc. IEEE 16th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2019, pp. 587–592.

[81] J. M. Hondzinski, L. Ikuma, M. de Queiroz, and C. Wang, "Effects of exoskeleton use on movement kinematics during performance of common work tasks: A case study," *Work*, vol. 61, no. 4, pp. 575–588, Jan. 2019.

[82] B. Choi, C. Seo, S. Lee, B. Kim, and D. Kim, "Swing control of a lower extremity exoskeleton using echo state networks," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 1328–1333, Jul. 2017.

[83] H. Inoue and T. Noritsugu, "Development of upper-limb power assist machine using linkage mechanism—Drive mechanism and its applications," *J. Robot. Mechatronics*, vol. 30, no. 2, pp. 214–222, Apr. 2018.

[84] S. Marcheschi, F. Salsedo, M. Fontana, and M. Bergamasco, "Body extender: Whole body exoskeleton for human power augmentation," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 611–616.

[85] M. Sato and E. Yagi, "A study on power assist suit using pneumatic actuators based on calculated retaining torques for lift-up motion," in *Proc. SICE Annu. Conf.* Tokyo, Japan: Society of Instrument and Control Engineers, Sep. 2011, pp. 628–632.

[86] A. Sergeyev, N. Alaraje, C. Seidel, Z. Carlson, and B. Breda, "Design of a pneumatically powered wearable exoskeleton with biomimetic support and actuation," in *Proc. IEEE Aerosp. Conf.*, Mar. 2013, pp. 1–8.

[87] H.-g. Kim, J.-w. Lee, J. Jang, C. Han, and S. Park, "Mechanical design of an exoskeleton for load-carrying augmentation," in *Proc. IEEE ISR*, Oct. 2013, pp. 1–5.

[88] Y. Naruoka, N. Hiramitsu, and Y. Mitsuya, "A study of power-assist technology to reduce body burden during loading and unloading operations by support of knee joint motion," *J. Robot. Mechatronics*, vol. 28, no. 6, pp. 949–957, Dec. 2016.

[89] Y. Zhu, G. Zhang, C. Zhang, G. Liu, and J. Zhao, "Biomechanical modeling and load-carrying simulation of lower limb exoskeleton," *Bio-Med. Mater. Eng.*, vol. 26, no. s1, pp. S729–S738, Aug. 2015.

[90] T. Bosch, J. van Eck, K. Knitel, and M. de Looze, "The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work," *Appl. Ergonom.*, vol. 54, pp. 212–217, May 2016.

[91] Y. Asano, K. Matsumoto, and H. Jinbo, "Response to assist torque failure of physical-assistant robots," in *Proc. 17th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2017, pp. 873–877.

[92] H. Yu, I. S. Choi, K.-L. Han, J. Y. Choi, G. Chung, and J. Suh, "Development of a stand-alone powered exoskeleton robot suit in steel manufacturing," *ISIJ Int.*, vol. 55, no. 12, pp. 2609–2617, 2015.

[93] D. J. Hyun, K. Bae, K. Kim, S. Nam, and D.-H. Lee, "A light-weight passive upper arm assistive exoskeleton based on multi-linkage spring-energy dissipation mechanism for overhead tasks," *Robot. Auto. Syst.*, vol. 122, Dec. 2019, Art. no. 103309.

[94] J. Nassour, S. Vaghani, and F. H. Hamker, "Design of soft exosuit for elbow assistance using butyl rubber tubes and textile," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2018, pp. 420–424.

[95] F. A. Panizzolo, I. Galiana, A. T. Asbeck, C. Siviy, K. Schmidt, K. G. Holt, and C. J. Walsh, "A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking," *J. NeuroEng. Rehabil.*, vol. 13, no. 1, pp. 1–14, May 2016.

[96] Y. G. Kim, K. Little, B. Noronha, M. Xiloyannis, L. Masia, and D. Accoto, "A voice activated bi-articular exosuit for upper limb assistance during lifting tasks," *Robot. Comput.-Integr. Manuf.*, vol. 66, Dec. 2020, Art. no. 101995.

[97] H.-S. Seong, D.-H. Kim, I. Gaponov, and J.-H. Ryu, "Development of a twisted string actuator-based exoskeleton for hip joint assistance in lifting tasks," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2020, pp. 761–767.

[98] R. K. P. S. Ranaweera, W. A. T. I. Jayasiri, W. G. D. Tharaka, J. H. H. P. Gunasiri, R. A. R. C. Gopura, T. S. S. Jayawardena, and G. K. I. Mann, "Anthro-X: Anthropomorphic lower extremity exoskeleton robot for power assistance," in *Proc. 4th Int. Conf. Control, Autom. Robot. (ICCAR)*, Apr. 2018, pp. 82–87.

[99] F. Sado, H. J. Yap, R. A. R. Ghazilla, and N. Ahmad, "Design and control of a wearable lower-body exoskeleton for squatting and walking assistance in manual handling works," *Mechatronics*, vol. 63, Nov. 2019, Art. no. 102272.

[100] Q. Yan, J. Zhang, and L. Zhou, "Kinematic analysis and simulation of a novel unpowered exoskeleton with parallel topology," in *Proc. IEEE 9th Annu. Int. Conf. CYBER Technol. Autom., Control, Intell. Syst. (CYBER)*, Jul. 2019, pp. 181–186.

[101] H. T. Tran, H. Cheng, H. Rui, X. Lin, M. K. Duong, and Q. Chen, "Evaluation of a fuzzy-based impedance control strategy on a powered lower exoskeleton," *Int. J. Social Robot.*, vol. 8, no. 1, pp. 103–123, Oct. 2015.

[102] C. Zhang, X. Zang, Z. Leng, H. Yu, J. Zhao, and Y. Zhu, "Human–machine force interaction design and control for the HIT load-carrying exoskeleton," *Adv. Mech. Eng.*, vol. 8, no. 4, Apr. 2016, Art. no. 168781401664506.

[103] H.-G. Kim, S. Park, and C. Han, "Design of a novel knee joint for an exoskeleton with good energy efficiency for load-carrying augmentation," *J. Mech. Sci. Technol.*, vol. 28, no. 11, pp. 4361–4367, Nov. 2014.

[104] D. Lim, W. Kim, H. Lee, H. Kim, K. Shin, T. Park, J. Lee, and C. Han, "Development of a lower extremity exoskeleton robot with a quasi-anthropomorphic design approach for load carriage," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2015, pp. 5345–5350.

[105] H. Kim, Y. J. Shin, and J. Kim, "Design and locomotion control of a hydraulic lower extremity exoskeleton for mobility augmentation," *Mechatronics*, vol. 46, pp. 32–45, Oct. 2017.

[106] H. Cao, J. Zhu, C. Xia, H. Zhou, X. Chen, and Y. Wang, "Design and control of a hydraulic-actuated leg exoskeleton for load-carrying augmentation," in *Intelligent Robotics and Applications*. Berlin, Germany: Springer, 2010, pp. 590–599.

[107] S. Krut, M. Benoit, E. Dombre, and F. Pierrot, "MoonWalker, a lower limb exoskeleton able to sustain bodyweight using a passive force balancer," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 2215–2220.

[108] R. B. Graham, E. M. Sadler, and J. M. Stevenson, "Does the personal lift-assist device affect the local dynamic stability of the spine during lifting?" *J. Biomech.*, vol. 44, no. 3, pp. 461–466, Feb. 2011.

[109] X. Li, T. Noritsugu, M. Takaiwa, and D. Sasaki, "Design of wearable power assist wear for low back support using pneumatic actuators," *Int. J. Autom. Technol.*, vol. 7, no. 2, pp. 228–236, Mar. 2013.

[110] H. Inose, K. Yokoyama, H. Imamura, I. Kikutani, and T. Nakamura, "Development of an endskeleton type power assist suit using pneumatic artificial muscles with amplification mechanism," in *Proc. IECON 41st Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2015, pp. 4708–4713.

[111] S. Hirotani, F. Cho, and T. Noritsugu, "Improvement of wearable power assist wear for low back support," in *Proc. Int. Conf. Multimedia Syst. Signal Process. (ICMSSP)*, Sep. 2016, pp. 90–94.

[112] I. Rosales, R. Lopez, H. Aguilar, A. O. Cordero, S. Salazar, and R. Lozano "Design and modelling of a backbone pneumatic exoskeleton," in *Proc. 18th Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Oct. 2014, pp. 927–933.

[113] S. R. Taal and Y. Sankai, "Exoskeletal spine and shoulder girdle for full body exoskeletons with human versatility," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 2217–2222.

[114] J.-H. Park, D. Zanotto, V. Vashista, X. Jin, P. Stegall, and S. K. Agrawal, "Second spine: A device to relieve stresses on the upper body during loaded walking," in *Proc. 5th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics*, Aug. 2014, pp. 689–694.

[115] U. L. S. Perera, N. P. Dasanayake, H. P. T. Hettiarachchi, M. A. V. A. Mannapperuma, R. K. P. S. Ranaweera, and R. A. R. C. Gopura, "HipExo: A hip exoskeleton robot for load lifting with flexible trunk linkage mechanism," in *Proc. Moratuwa Eng. Res. Conf. (MERCon)*, Jul. 2020, pp. 614–619.

[116] H. Inose, S. Mohri, Y. Yamada, T. Nakamura, K. Yokoyama, and I. Kikutani, "Effective motion assistance using a passive force endoskeleton power assist suit," in *Proc. IECON 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2016, pp. 542–547.

[117] W. Christine, H. Victor, O. Daryl, F. Todd, and F. Tyler, "A patient-specific lower extremity biomechanical analysis of a knee orthotic during a deep squat movement," *Med. Eng. Phys.*, vol. 80, pp. 1–7, Jun. 2020.

[118] A. S. Koopman, M. Näf, S. J. Baltrusch, I. Kingma, C. Rodriguez-Guerrero, J. Babič, M. P. de Looze, and J. H. van Dieën, "Biomechanical evaluation of a new passive back support exoskeleton," *J. Biomech.*, vol. 105, May 2020, Art. no. 109795.

[119] J.-H. Park, P. Stegall, D. Zanotto, V. Vashista, X. Jin, and S. K. Agrawal, "Design of the second spine: A secondary pathway to transfer loads from the shoulders to the pelvis," in *Proc. 37th Mech. Robot. Conf.*, vol. 6B, Aug. 2013, Art. no. V06BT07A008.

[120] M. Lazzaroni, S. Toxiri, D. G. Caldwell, S. Anastasi, L. Monica, E. D. Momi, and J. Ortiz, "Acceleration-based assistive strategy to control a back-support exoskeleton for load handling: Preliminary evaluation," in *Proc. IEEE 16th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2019, pp. 625–630.

[121] M. J. Deng, Z. Wang, H. H. He, and Y. Xue, "Design and weight lifting analysis of a strengthen upper limb exoskeleton robot," *Appl. Mech. Mater.*, vol. 437, pp. 695–699, Oct. 2013.

[122] Y. G. Kim, M. Xiloyannis, D. Accoto, and L. Masia, "Development of a soft exosuit for industrial applications," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 324–329.

[123] A. Mauri, J. Lettori, G. Fusi, D. Fausti, M. Mor, F. Braghin, G. Legnani, and L. Roveda, "Mechanical and control design of an industrial exoskeleton for advanced human empowering in heavy parts manipulation tasks," *Robotics*, vol. 8, no. 3, p. 65, Aug. 2019.

[124] D. Park and K.-J. Cho, "Development and evaluation of a soft wearable weight support device for reducing muscle fatigue on shoulder," *PLoS ONE*, vol. 12, no. 3, Mar. 2017, Art. no. e0173730.

[125] R. J. L. Macke, A. Q. L. Keemink, and A. H. A. Stienen, "Passive lower back moment support in a wearable lifting aid: Counterweight versus springs," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2016, pp. 445–449.

[126] Y. Muramatsu, H. Kobayashi, Y. Sato, H. Jiaou, T. Hashimoto, and H. Kobayashi, "Quantitative performance analysis of exoskeleton augmenting devices–muscle suit–for manual worker," *Int. J. Autom. Technol.*, vol. 5, no. 4, pp. 559–567, Jul. 2011.

[127] B. Ugurlu, M. Nishimura, K. Hyodo, M. Kawanishi, and T. Narikiyo, "A framework for sensorless torque estimation and control in wearable exoskeletons," in *Proc. 12th IEEE Int. Workshop Adv. Motion Control (AMC)*, Mar. 2012, pp. 1–7.

[128] H. Lee, B. Lee, W. Kim, M. Gil, J. Han, and C. Han, "Human-robot cooperative control based on pHRI (physical human-robot interaction) of exoskeleton robot for a human upper extremity," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 6, pp. 985–992, May 2012.

[129] Z. Tang, K. Zhang, S. Sun, Z. Gao, L. Zhang, and Z. Yang, "An upper-limb power-assist exoskeleton using proportional myoelectric control," *Sensors*, vol. 14, no. 4, pp. 6677–6694, Apr. 2014.

[130] D. Cha, S. N. Oh, H. H. Lee, K.-S. Kim, K. I. Kim, and S. Kim, "Design and evaluation of the unmanned technology research center exoskeleton implementing the precedence walking assistance mechanism," *J. Electr. Eng. Technol.*, vol. 10, no. 6, pp. 2376–2383, Nov. 2015.

[131] Y. Long, Z.-J. Du, C.-F. Chen, W.-D. Wang, L. He, X.-W. Mao, G.-Q. Xu, G.-Y. Zhao, and W. Dong, "Hybrid control scheme of a hydraulically actuated lower extremity exoskeleton for load-carrying," *J. Intell. Robotic Syst.*, vol. 91, nos. 3–4, pp. 493–500, Sep. 2017.

[132] Y. Ding, I. Galiana, A. T. Asbeck, S. M. M. De Rossi, J. Bae, T. R. T. Santos, V. L. de Araujo, S. Lee, K. G. Holt, and C. Walsh, "Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 2, pp. 119–130, Feb. 2017.

[133] M. Kashima, H. Arakawa, S. Kimura, R. Nishihama, K. Yokoyama, I. Kikutani, and T. Nakamura, "Development of assist suit for squat lifting support considering gait and quantitative evaluation by three-dimensional motion analysis," *J. Robot. Mechatronics*, vol. 32, no. 1, pp. 209–219, Feb. 2020.

[134] C.-Y. Cheng, S. Okamoto, P. Li, Y. Akiyama, C. Qiu, and Y. Yamada, "Encouragement of squat-lifting: Feasibility study of a highly usable passive knee assistive device," in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Jan. 2020, pp. 504–508.

[135] T. Zhang and H. Huang, "A lower-back robotic exoskeleton: Industrial handling augmentation used to provide spinal support," *IEEE Robot. Autom. Mag.*, vol. 25, no. 2, pp. 95–106, Jun. 2018.

[136] S. Toxiri, J. Ortiz, J. Masood, J. Fernández, L. A. Mateos, and D. G. Caldwell, "A wearable device for reducing spinal loads during lifting tasks: Biomechanics and design concepts," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2015, pp. 2295–2300.

[137] J. Masood, J. Ortiz, J. Fernández, L. A. Mateos, and D. G. Caldwell, "Mechanical design and analysis of light weight hip joint parallel elastic actuator for industrial exoskeleton," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 631–636.

[138] S. Toxiri, J. Ortiz, J. Masood, J. Fernández, L. A. Mateos, and D. G. Caldwell, "A powered low-back exoskeleton for industrial handling: Considerations on controls," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2016, pp. 287–291.

[139] K. S. Stadler, R. Altenburger, E. Schmidhauser, D. Scherly, J. Ortiz, S. Toxiri, L. Mateos, and J. Masood, "Robo-mate an exoskeleton for industrial use—Concept and mechanical design," in *Advances in Cooperative Robotics*. Singapore: World Scientific, Aug. 2016, pp. 806–813.

[140] S. Toxiri, J. Ortiz, and D. G. Caldwell, "Assistive strategies for a back support exoskeleton: Experimental evaluation," in *Advances in Service and Industrial Robotics*. Cham, Switzerland: Springer, Jul. 2017, pp. 805–812.

[141] S. Toxiri, A. S. Koopman, M. Lazzaroni, J. Ortiz, V. Power, M. P. de Looze, L. O'Sullivan, and D. G. Caldwell, "Rationale, implementation and evaluation of assistive strategies for an active back-support exoskeleton," *Frontiers Robot. AI*, vol. 5, p. 53, May 2018.

[142] S. Toxiri, T. Verstraten, A. Calanca, D. G. Caldwell, and J. Ortiz, "Using parallel elasticity in back-support exoskeletons: A study on energy consumption during industrial lifting tasks," in *Proc. Wearable Robot. Assoc. Conf. (WearRAcon)*, Mar. 2019, pp. 1–6.

[143] T. Poliero, S. Toxiri, S. Anastasi, L. Monica, D. G. Caldwell, and J. Ortiz, "Assessment of an on-board classifier for activity recognition on an active back-support exoskeleton," in *Proc. IEEE 16th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2019, pp. 559–564.

[144] K. Miura, H. Kadone, M. Koda, T. Abe, H. Endo, H. Murakami, M. Doita, H. Kumagai, K. Nagashima, K. Fujii, H. Noguchi, T. Funayama, H. Kawamoto, Y. Sankai, and M. Yamazaki, "The hybrid assisted limb (HAL) for care support, a motion assisting robot providing exoskeletal lumbar support, can potentially reduce lumbar load in repetitive snow-shoveling movements," *J. Clin. Neurosci.*, vol. 49, pp. 83–86, Mar. 2018.

[145] K. Miura, H. Kadone, M. Koda, T. Abe, H. Kumagai, K. Nagashima, K. Mataki, K. Fujii, H. Noguchi, T. Funayama, H. Kawamoto, Y. Sankai, and M. Yamazaki, "The hybrid assistive limb (HAL) for care support successfully reduced lumbar load in repetitive lifting movements," *J. Clin. Neurosci.*, vol. 53, pp. 276–279, Jul. 2018.

[146] A. von Glinski, E. Yilmaz, S. Mrotzek, E. Marek, B. Jettkant, A. Brinkemper, C. Fisahn, T. A. Schildhauer, and J. Geßmann, "Effectiveness of an on-body lifting aid (HAL for care support) to reduce lower back muscle activity during repetitive lifting tasks," *J. Clin. Neurosci.*, vol. 63, pp. 249–255, May 2019.

[147] C. K. Tan, H. Kadone, K. Miura, T. Abe, M. Koda, M. Yamazaki, Y. Sankai, and K. Suzuki, "Muscle synergies during repetitive stoop lifting with a bioelectrically-controlled lumbar support exoskeleton," *Frontiers Hum. Neurosci.*, vol. 13, p. 142, Apr. 2019.

[148] H. K. Kim, M. Hussain, J. Park, J. Lee, and J. W. Lee, "Analysis of active back-support exoskeleton during manual load-lifting tasks," *J. Med. Biol. Eng.*, vol. 41, pp. 704–714, 2021. [Online]. Available: https://api.semanticscholar.org/CorpusID:238781464

[149] T. Tsuji, S. Miyata, T. Hashimoto, and H. Kobayashi, "Controller design for robot with pneumatic artificial muscles," in *Proc. SICE-ICASE Int. Joint Conf.*, Oct. 2006, pp. 5419–5422.

[150] T. Aida, H. Nozaki, and H. Kobayashi, "Development of muscle suit and application to factory laborers," in *Proc. Int. Conf. Mechatronics Autom.*, Aug. 2009, pp. 1027–1032.

[151] R. Baud, A. Ortlieb, J. Olivier, M. Bouri, and H. Bleuler, "HIBSO hip exoskeleton: Toward a wearable and autonomous design," in *Proc. Int. Workshop Med. Service Robots*. Cham, Switzerland: Springer, 2016, pp. 185–195.

[152] M. Ide, T. Hashimoto, K. Matsumoto, and H. Kobayashi, "Evaluation of the power assist effect of muscle suit for lower back support," *IEEE Access*, vol. 9, pp. 3249–3260, 2021.

[153] J. Nassour, G. Zhao, and M. Grimmer, "Soft pneumatic elbow exoskeleton reduces the muscle activity, metabolic cost and fatigue during holding and carrying of loads," *Sci. Rep.*, vol. 11, no. 1, Jun. 2021, Art. no. 12556.

[154] D. M. Frost, M. Abdoli-E, and J. M. Stevenson, "PLAD (personal lift assistive device) stiffness affects the lumbar flexion/extension moment and the posterior chain EMG during symmetrical lifting tasks," *J. Electromyogr. Kinesiol.*, vol. 19, no. 6, pp. e403–e412, Dec. 2009.

[155] M. B. Näf, A. S. Koopman, S. Baltrusch, C. Rodriguez-Guerrero, B. Vanderborght, and D. Lefeber, "Passive back support exoskeleton improves range of motion using flexible beams," *Frontiers Robot. AI*, vol. 5, p. 115, Jun. 2018.

[156] E. P. Lamers, A. J. Yang, and K. E. Zelik, "Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 8, pp. 1674–1680, Aug. 2018.

[157] X. Qu, C. Qu, T. Ma, P. Yin, N. Zhao, Y. Xia, and S. Qu, "Effects of an industrial passive assistive exoskeleton on muscle activity, oxygen consumption and subjective responses during lifting tasks," *PLoS ONE*, vol. 16, no. 1, Jan. 2021, Art. no. e0245629.

[158] P. Yin, L. Yang, and S. Qu, "Development of an ergonomic wearable robotic device for assisting manual workers," *Int. J. Adv. Robotic Syst.*, vol. 18, no. 5, Sep. 2021, Art. no. 172988142110467.

[159] S.-S. Yun, K. Kim, J. Ahn, and K.-J. Cho, "Body-powered variable impedance: An approach to augmenting humans with a passive device by reshaping lifting posture," *Sci. Robot.*, vol. 6, no. 57, Aug. 2021, Art. no. eabe1243.

[160] M. Goršič, Y. Song, B. Dai, and D. Novak, "Evaluation of the HeroWear apex back-assist exosuit during multiple brief tasks," *J. Biomech.*, vol. 126, Sep. 2021, Art. no. 110620.

[161] D. P. Losey, C. G. McDonald, E. Battaglia, and M. K. O'Malley, "A review of intent detection, arbitration, and communication aspects of shared control for physical human–robot interaction," *Appl. Mech. Rev.*, vol. 70, no. 1, Jan. 2018, Art. no. 010804.

[162] Y. Muramatsu, H. Kobayashi, Y. Sato, H. Jiaou, T. Hashimoto, and H. Kobayashi, "Quantitative performance analysis of muscle suit—Estimation by oxyhemoglobin and deoxyhemoglobin," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Dec. 2011, pp. 293–298.

[163] S. J. Baltrusch, J. H. van Dieën, S. M. Bruijn, A. S. Koopman, C. A. M. van Bennekom, and H. Houdijk, "The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking," *Ergonomics*, vol. 62, no. 7, pp. 903–916, Apr. 2019.

[164] G. Winter, C. Felten, and J. Hedtmann, "Testing of exoskeletons in the context of logistics—Application and limits of use," in *Communications in Computer and Information Science*. Cham, Switzerland: Springer, 2019, pp. 265–270.

[165] S. J. Baltrusch, J. H. van Dieën, A. S. Koopman, M. B. Näf, C. Rodriguez-Guerrero, J. Babič, and H. Houdijk, "SPEXOR passive spinal exoskeleton decreases metabolic cost during symmetric repetitive lifting," *Eur. J. Appl. Physiol.*, vol. 120, no. 2, pp. 401–412, Dec. 2019.

[166] Y. S. Zhang, Z. Y. Yang, G. S. Wu, and J. Zhang, "Mechanical design of power assist exoskeleton suit NES-3 based on backstay cable," *Appl. Mech. Mater.*, vols. 40–41, pp. 1016–1021, Nov. 2010.

[167] Y. Sato, J. He, H. Kobayashi, Y. Muramatsu, T. Hashimoto, and H. Kobayashi, "Development and quantitative performance estimation of the back support muscle suit," *Trans. Jpn. Soc. Mech. Eng. Ser. C*, vol. 78, no. 792, pp. 2987–2999, 2012.

[168] S. N. Yu, H. D. Lee, S. H. Lee, W. S. Kim, J. S. Han, and C. S. Han, "Design of an under-actuated exoskeleton system for walking assist while load carrying," *Adv. Robot.*, vol. 26, nos. 5–6, pp. 561–580, Jan. 2012.

[169] Q. Guo, X. gang Zhang, D. Jiang, and L. lu Zhang, "Hydraulic pressure control system simulation and performance test of lower extremity exoskeleton," in *Social Robotics*. Berlin, Germany: Springer, 2012, pp. 612–620.

[170] Y. Zhu, J. Cui, and J. Zhao, "Biomimetic design and biomechanical simulation of a 15-DOF lower extremity exoskeleton," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2013, pp. 1119–1124.

[171] W. S. Kim, H. D. Lee, D. H. Lim, C. S. Han, and J. S. Han, "Development of a lower extremity exoskeleton system for walking assistance while load carrying," in *Proc. Nature-Inspired Mobile Robot.*, Jul. 2013, pp. 35–42.

[172] Y. Miao, F. Gao, and D. Pan, "Prototype design and size optimization of a hybrid lower extremity exoskeleton with a scissor mechanism for load-carrying augmentation," *Proc. Inst. Mech. Eng., C, J. Mech. Eng. Sci.*, vol. 229, no. 1, pp. 155–167, Apr. 2014.

[173] J.-H. Park, X. Jin, and S. K. Agrawal, "Compensating inertia forces during human load carrying using a motorized second spine," in *Proc. 38th Mech. Robot. Conf.*, vol. 5B, 2014, Art. no. V05BT08A009.

[174] Y. Şahin, F. M. Botsalı, M. Kalyoncu, M. Tinkir, Ü. Önen, N. Yılmaz, and A. Çakan, "Mechanical design of lower extremity exoskeleton assisting walking of load carrying human," *Appl. Mech. Mater.*, vol. 598, pp. 141–145, Jul. 2014.

[175] J.-W. Lee, H. Kim, J. Jang, and S. Park, "Virtual model control of lower extremity exoskeleton for load carriage inspired by human behavior," *Auto. Robots*, vol. 38, no. 2, pp. 211–223, Jul. 2014.

[176] H. Kim, C. Seo, Y. J. Shin, J. Kim, and Y. S. Kang, "Locomotion control strategy of hydraulic lower extremity exoskeleton robot," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2015, pp. 577–582.

[177] R. Huang, H. Cheng, Q. Chen, H.-T. Tran, and X. Lin, "Interactive learning for sensitivity factors of a human-powered augmentation lower exoskeleton," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2015, pp. 6409–6415.

[178] S. Yu, H. Lee, W. Kim, and C. Han, "Development of an underactuated exoskeleton for effective walking and load-carrying assist," *Adv. Robot.*, vol. 30, no. 8, pp. 535–551, Feb. 2016.

[179] Y. Zhu, G. Zhang, H. Li, and J. Zhao, "Automatic load-adapting passive upper limb exoskeleton," *Adv. Mech. Eng.*, vol. 9, no. 9, Sep. 2017, Art. no. 168781401772994.

[180] I. Rosales, R. Lopez, H. Aguilar, Y. Rosales, A. O. Cordero, S. Salazar, and R. Lozano, "Pneumatic assistant of one degree of freedom for lifting," in *Proc. 19th Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Oct. 2015, pp. 249–254.

[181] H. Zhang, A. Kadrolkar, and F. C. Sup, "Design and preliminary evaluation of a passive spine exoskeleton," *J. Med. Devices*, vol. 10, no. 1, Nov. 2015, Art. no. 011002.

[182] T. Fujita and Y. Sankai, "Development of motion control algorithm for upper limb support system based on bioelectrical signals for heavy work over head," in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Dec. 2015, pp. 181–186.

[183] A. Ohno, H. Nabae, and K. Suzumori, "Static analysis of powered low-back orthosis driven by thin pneumatic artificial muscles considering body surface deformation," in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Dec. 2015, pp. 39–44.

[184] Y. Ding, I. Galiana, C. Siviy, F. A. Panizzolo, and C. Walsh, "IMU-based iterative control for hip extension assistance with a soft exosuit," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2016, pp. 3501–3508.

[185] R. Meattini, G. Palli, and C. Melchiorri, "Experimental evaluation of a sEMG-based control for elbow wearable assistive devices during load lifting tasks," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 140–145.

[186] P. Malcolm, S. Lee, S. Crea, C. Siviy, F. Saucedo, I. Galiana, F. A. Panizzolo, K. G. Holt, and C. J. Walsh, "Varying negative work assistance at the ankle with a soft exosuit during loaded walking," *J. NeuroEng. Rehabil.*, vol. 14, no. 1, pp. 1–12, Jun. 2017.

[187] S. Lee, J. Kim, L. Baker, A. Long, N. Karavas, N. Menard, I. Galiana, and C. J. Walsh, "Autonomous multi-joint soft exosuit with augmentation-power-based control parameter tuning reduces energy cost of loaded walking," *J. NeuroEng. Rehabil.*, vol. 15, no. 1, pp. 1–9, Jul. 2018.

[188] S. Mohri, H. Inose, K. Yokoyama, Y. Yamada, I. Kikutani, and T. Nakamura, "Development of endoskeleton type knee auxiliary power assist suit using pneumatic artificial muscles," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2016, pp. 107–112.

[189] S. Mohri, H. Inose, H. Arakawa, K. Yokoyama, Y. Yamada, I. Kikutani, and T. Nakamura, "Development of non-rotating joint drive type gastrocnemius-reinforcing power assist suit for squat lifting," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2017, pp. 851–856.

[190] S. Mohri, H. Inose, H. Arakawa, K. Yokoyama, Y. Yamada, I. Kikutani, and T. Nakamura, "Proposal of non-rotating joint drive type high output power assist suit for squat lifting," in *Proc. 26th IEEE Int. Symp. Robot Hum. Interact. Commun. (RO-MAN)*, Aug. 2017, pp. 1222–1227.

[191] F. Cho, X. Li, and T. Noritsugu, "Development of wearable power assist wear using pneumatic actuators," in *Proc. 3rd Int. Conf. Intell. Technol. Eng. Syst. (ICITES)*. Cham, Switzerland: Springer, 2016, pp. 461–468.

[192] F. Cho, R. Sugimoto, T. Noritsugu, and X. Li, "Improvement of wearable power assist wear for low back support using pneumatic actuator," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 249, Oct. 2017, Art. no. 012004.

[193] T. Inoue, S. Nomura, Y. Takahashi, M. Kawai, and Y. Taniai, "Leg control based on human motion prediction using motion sensor for power assist suit without binding knee," in *Proc. IEEE Congr. Evol. Comput. (CEC)*, Jul. 2016, pp. 1720–1726.

[194] Y. Long, Z.-J. Du, W.-D. Wang, and W. Dong, "Robust sliding mode control based on GA optimization and CMAC compensation for lower limb exoskeleton," *Appl. Bionics Biomech.*, vol. 2016, pp. 1–13, Feb. 2016.

[195] S. Song, X. Zhang, Q. Li, H. Fang, Q. Ye, and Z. Tan, "Dynamic analysis and design of lower extremity power-assisted exoskeleton," in *Wearable Sensors Robots*. Singapore: Springer, Oct. 2016, pp. 145–164.

[196] N. Mir-Nasiri, "Efficient lower limb exoskeleton for human motion assistance," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2016, pp. 293–297.

[197] T. G. Sugar, E. Fernandez, D. Kinney, K. W. Hollander, and S. Redkar, "HeSA, hip exoskeleton for superior assistance," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2016, pp. 319–323.

[198] S. J. Baltrusch, J. H. van Dieën, S. M. Bruijn, A. S. Koopman, C. A. M. van Bennekom, and H. Houdijk, "The effect of a passive trunk exoskeleton on functional performance and metabolic costs," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2018, pp. 229–233.

[199] A. S. Koopman, I. Kingma, M. P. de Looze, and J. H. van Dieën, "Effects of a passive back exoskeleton on the mechanical loading of the low-back during symmetric lifting," *J. Biomech.*, vol. 102, Mar. 2020, Art. no. 109486.

[200] M. M. Alemi, S. Madinei, S. Kim, D. Srinivasan, and M. A. Nussbaum, "Effects of two passive back-support exoskeletons on muscle activity, energy expenditure, and subjective assessments during repetitive lifting," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 62, no. 3, pp. 458–474, Feb. 2020.

[201] Y. Liu, Y. Gao, and Y. Zhu, "A novel cable-pulley underactuated lower limb exoskeleton for human load-carrying walking," *J. Mech. Med. Biol.*, vol. 17, no. 7, Nov. 2017, Art. no. 1740042.

[202] Y. Liu, Y. Gao, F. Xiao, and J. Zhao, "Research on the cable-pulley underactuated lower limb exoskeleton," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2017, pp. 577–583.

[203] M. Canesi, M. Xiloyannis, A. Ajoudani, A. Bicchi, and L. Masia, "Modular one-to-many clutchable actuator for a soft elbow exosuit," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 1679–1685.

[204] B. K. Dinh, M. Xiloyannis, C. W. Antuvan, L. Cappello, and L. Masia, "Hierarchical cascade controller for assistance modulation in a soft wearable arm exoskeleton," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1786–1793, Jul. 2017.

[205] H. Jitosho and F. Fujii, "A reference augmentation design for the adaptive control of a wearable assist robot powered by the Mckibben actuator," in *Proc. IEEE Int. Conf. Syst. Man, Cybern. (SMC)*, Oct. 2017, pp. 1099–1104.

[206] K. Junius, M. Degelaen, N. Lefeber, E. Swinnen, B. Vanderborght, and D. Lefeber, "Bilateral, misalignment-compensating, full-DOF hip exoskeleton: Design and kinematic validation," *Appl. Bionics Biomech.*, vol. 2017, pp. 1–14, Jul. 2017.

[207] E. Nakamura, K. Ichinose, and H. Kobayashi, "Development and evaluation of muscle suit for arms and lower back support," in *Proc. 17th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2017, pp. 1462–1465.

[208] S. Kondo, R. Ikeura, A. Tachi, K. Murakami, S. Hayakawa, and K. Yasuda, "Development and evaluation of Waist assist device for shipbuilding tasks," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2017, pp. 1642–1647.

[209] P. Stelzer, B. Otten, W. Kraus, and A. Pott, "Sensor and control concept for a wearable robot for manual load handling assistance," in *New Trends Med. Service Robots*. Cham, Switzerland: Springer, Jul. 2017, pp. 87–100.

[210] F. Durante, M. G. Antonelli, and P. B. Zobel, "Development of an active exoskeleton for assisting back movements in lifting weights," *Int. J. Mech. Eng. Robot. Res.*, vol. 7, no. 4, pp. 353–360, 2018.

[211] B. Chen, L. Grazi, F. Lanotte, N. Vitiello, and S. Crea, "A real-time lift detection strategy for a hip exoskeleton," *Frontiers Neurorobotics*, vol. 12, p. 17, Apr. 2018.

[212] B. Chen, L. Grazi, F. Lanotte, N. Vitiello, and S.Crea, "Lift movement detection with a QDA classifier for an active hip exoskeleton," in *Biosystems Biorobotics*. Cham, Switzerland: Springer, Oct. 2018, pp. 224–228.

[213] R. Mallat, V. Bonnet, W. Huo, P. Karasinski, Y. Amirat, M. Khalil, and S. Mohammed, "Human-exoskeleton system dynamics identification using affordable sensors," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 6759–6765.

[214] S. S. Kawale and M. Sreekumar, "Design of a wearable lower body exoskeleton mechanism for shipbuilding industry," *Proc. Comput. Sci.*, vol. 133, pp. 1021–1028, Jan. 2018.

[215] Q. Chen, H. Cheng, W. Shen, R. Huang, and X. Chen, "Hybrid control for human-powered augmentation exoskeleton," in *Proc. IEEE 8th Annu. Int. Conf. CYBER Technol. Autom., Control, Intell. Syst. (CYBER)*, Jul. 2018, pp. 682–687.

[216] Y. Ishizuka, S. Murai, Y. Takahashi, M. Kawai, Y. Taniai, and T. Naniwa, "Modeling walking behavior of powered exoskeleton based on complex-valued neural network," in *Proc. IEEE Int. Conf. Syst. Man, Cybern. (SMC)*, Oct. 2018, pp. 1927–1932.

[217] H. Arakawa, S. Mohri, K. Yokoyama, Y. Yamada, I. Kikutani, and T. Nakamura, "Proposal of non-rotating joint drive type mechanical assist device for squat lifting by using leaf and compression spring," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 330–335.

[218] H. Li, W. Cheng, F. Liu, M. Zhang, and K. Wang, "The effects on muscle activity and discomfort of varying load carriage with and without an augmentation exoskeleton," *Appl. Sci.*, vol. 8, no. 12, p. 2638, Dec. 2018.

[219] S. Kudernatsch and D. R. Peterson, "Biomechanical testing of an upper-extremity occupational exoskeleton–preliminary report on methodologies and pilot data," *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 62, no. 1, pp. 2013–2017, Sep. 2018.

[220] C. M. Thalman, Q. P. Lam, P. H. Nguyen, S. Sridar, and P. Polygerinos, "A novel soft elbow exosuit to supplement bicep lifting capacity," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 6965–6971.

[221] K. Ogawa, A. Ono, Y. Fukuda, K. Tsuneyasu, and Y. Kurita, "Development of a lightweight flexible construction work assist suit using pneumatic rubber artificial muscles," in *Proc. 40th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2018, pp. 4389–4392.

[222] Y.-T. Liao, K. Kodama, T. Ishioka, H.-H. Lee, and E. Tanaka, "Development and evaluation of a worker-wear assistance suit with the adjustable and concealable elastic structure for the manual handling workers," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2018, pp. 1252–1256.

[223] R. Puerta, A. Lopez, L. Roldan, and D. Patino, "Control of 1-DOF exoskeleton based on neural network regression analysis and wavelet transform of MES," in *Proc. IEEE 4th Colombian Conf. Autom. Control (CCAC)*, Oct. 2019, pp. 1–6.

[224] M. R. U. Islam and S. Bai, "Payload estimation using forcemyography sensors for control of upper-body exoskeleton in load carrying assistance," *Model., Identificat. Control, A Norwegian Res. Bull.*, vol. 40, no. 4, pp. 189–198, 2019.

[225] M. Han, T. Li, S. Wang, T. Ma, and N. Ai, "Design of a booster exoskeleton for lumbar spine protection of physical workers," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2019, pp. 1525–1529.

[226] Y.-T. Liao, T. Ishioka, K. Mishima, C. Kanda, K. Kodama, and E. Tanaka, "Development of a close-fitting assistive suit with adjustable structure for arm and back as needed–e.z.UP," in *Robot. Mechatronics*. Cham, Switzerland: Springer, Sep. 2019, pp. 371–379.

[227] M. T. Picchiotti, E. B. Weston, G. G. Knapik, J. S. Dufour, and W. S. Marras, "Impact of two postural assist exoskeletons on biomechanical loading of the lumbar spine," *Appl. Ergonom.*, vol. 75, pp. 1–7, Feb. 2019.

[228] L. Xia, Y. Feng, L. Zheng, C. Wang, and X. Wu, "Development of an adaptive iterative learning controller with sensorless force estimator for the hip-type exoskeleton," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2019, pp. 2516–2521.

[229] R. Ramon, C. Nataros, T. Yi, L. Lagos, A. Avarelli, and O. Bai, "Hotcell worker assistive robotic exoskeleton design and control," in *Proc. IEEE Int. Symp. Meas. Control Robot. (ISMCR)*, Sep. 2019, pp. A1-3-1-A1-3-4.

[230] S. Yu, T.-H. Huang, D. Wang, B. Lynn, D. Sayd, V. Silivanov, Y. S. Park, Y. Tian, and H. Su, "Design and control of a high-torque and highly backdrivable hybrid soft exoskeleton for knee injury prevention during squatting," *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 4579–4586, Oct. 2019.

[231] J.-W. Lee and G. Kim, "Design and control of a lifting assist device for preventing lower back injuries in industrial athletes," *Int. J. Precis. Eng. Manuf.*, vol. 20, no. 10, pp. 1825–1838, Jun. 2019.

[232] M. Kashima, H. Arakawa, S. Kimura, R. Nishihama, K. Yokoyama, I. Kikutani, and T. Nakamura, "Proposal of passive type power assist suit for squat lifting considering walking," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2019, pp. 114–119.

[233] Z. Ya, A. Peng, Y. He, X. Ma, C. Wang, and X. Wu, "Development of a non-power Waist assist device and IEMG-based evaluation of assist effect," in *Proc. IEEE 4th Int. Conf. Adv. Robot. Mechatronics (ICARM)*, Jul. 2019, pp. 99–104.

[234] W. Wei, W. Wang, Z. Qu, J. Gu, X. Lin, and C. Yue, "The effects of a passive exoskeleton on muscle activity and metabolic cost of energy," *Adv. Robot.*, vol. 34, no. 1, pp. 19–27, Dec. 2019.

[235] W. Wei, S. Zha, Y. Xia, J. Gu, and X. Lin, "A hip active assisted exoskeleton that assists the semi-squat lifting," *Appl. Sci.*, vol. 10, no. 7, p. 2424, Apr. 2020.

[236] H.-J. Kim, D.-H. Lim, W.-S. Kim, and C.-S. Han, "Development of a passive modular knee mechanism for a lower limb exoskeleton robot and its effectiveness in the workplace," *Int. J. Precis. Eng. Manuf.*, vol. 21, no. 2, pp. 227–236, Dec. 2019.

[237] F. A. Panizzolo, G. M. Freisinger, N. Karavas, A. M. Eckert-Erdheim, C. Siviy, A. Long, R. A. Zifchock, M. E. LaFiandra, and C. J. Walsh, "Metabolic cost adaptations during training with a soft exosuit assisting the hip joint," *Sci. Rep.*, vol. 9, no. 1, p. 9779, Jul. 2019.

[238] R. Zhang, Y. Zhu, H. Li, N. Lin, and J. Zhao, "Development of a parallel-structured upper limb exoskeleton for lifting assistance," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2019, pp. 307–312.

[239] A. Zhu, Z. Shen, H. Shen, Y. Tu, H. Mao, X. Zhang, and G. Cao, "Design of a passive shoulder lifting exoskeleton of human-machine multi-link," in *Proc. 16th Int. Conf. Ubiquitous Robots (UR)*, Jun. 2019, pp. 723–727.

[240] W. Shin, G. Park, Y. Lee, J. Lee, and J. Kim, "Development and validation of pneumatic muscle based back assistance exoskeleton," in *Proc. 16th Int. Conf. Ubiquitous Robots (UR)*, Jun. 2019, pp. 349–353.

[241] B. Choi, C. Seo, S. Lee, and B. Kim, "Control of power-augmenting lower extremity exoskeleton while walking with heavy payload," *Int. J. Adv. Robotic Syst.*, vol. 16, no. 1, Jan. 2019, Art. no. 172988141983053.

[242] I. Kang, H. Hsu, and A. Young, "The effect of hip assistance levels on human energetic cost using robotic hip exoskeletons," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 430–437, Apr. 2019.

[243] M. H. Tran, P. Kmecl, Y. Regmi, B. Dai, M. Goršic, and D. Novak, "Toward real-world evaluations of trunk exoskeletons using inertial measurement units," in *Proc. IEEE 16th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2019, pp. 483–487.

[244] X. Yong, Z. Yan, C. Wang, C. Wang, N. Li, and X. Wu, "Ergonomic mechanical design and assessment of a Waist assist exoskeleton for reducing lumbar loads during lifting task," *Micromachines*, vol. 10, no. 7, p. 463, Jul. 2019.

[245] Z. Yao, C. Linnenberg, R. Weidner, and J. Wulfsberg, "Development of a soft power suit for lower back assistance," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, May 2019, pp. 5103–5109.

[246] Ž. Kozinc, S. Baltrusch, H. Houdijk, and N. Šarabon, "Short-term effects of a passive spinal exoskeleton on functional performance, discomfort and user satisfaction in patients with low back pain," *J. Occupational Rehabil.*, vol. 31, no. 1, pp. 142–152, Apr. 2020.

[247] Ž. Kozinc, S. Baltrusch, H. Houdijk, and N. Šarabon, "Reliability of a battery of tests for functional evaluation of trunk exoskeletons," *Appl. Ergonom.*, vol. 86, Jul. 2020, Art. no. 103117.

[248] X. Yang, T.-H. Huang, H. Hu, S. Yu, S. Zhang, X. Zhou, A. Carriero, G. Yue, and H. Su, "Spine-inspired continuum soft exoskeleton for stoop lifting assistance," *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 4547–4554, Oct. 2019.

[249] S. J. Park and C. H. Park, "Suit-type wearable robot powered by Shape-memory-alloy-based fabric muscle," *Sci. Rep.*, vol. 9, no. 1, p. 9157, Jun. 2019.

[250] E. Panero, G. G. Muscolo, S. Pastorelli, and L. Gastaldi, "Model based analysis of trunk exoskeleton for human efforts reduction," in *Advances in Service and Industrial Robotics*. Cham, Switzerland: Springer, May 2019, pp. 410–418.

[251] E. Panero, G. G. Muscolo, L. Gastaldi, and S. Pastorelli, "Multibody analysis of a 3D human model with trunk exoskeleton for industrial applications," in *Multibody Dynamics 2019*. Cham, Switzerland: Springer, Jun. 2019, pp. 43–51.

[252] B. Treussart, F. Geffard, N. Vignais, and F. Marin, "Controlling an exoskeleton with EMG signal to assist load carrying: A personalized calibration," in *Proc. Int. Conf. Mechatronics, Robot. Syst. Eng. (MoRSE)*, Dec. 2019, pp. 246–252.

[253] D. Cha and K. I. Kim, "A lower limb exoskeleton based on recognition of lower limb walking intention," *Trans. Can. Soc. Mech. Eng.*, vol. 43, no. 1, pp. 102–111, Mar. 2019.

[254] M. M. Alemi, J. Geissinger, A. A. Simon, S. E. Chang, and A. T. Asbeck, "A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting," *J. Electromyogr. Kinesiol.*, vol. 47, pp. 25–34, Aug. 2019.

[255] I. Rosales-Dìaz, J. R. López-Gutiérrez, A. E. Z. Suárez, S. R. Salazar, A. Osorio-Cordero, H. Aguilar-Sierra, and R. Lozano, "Comparison of control techniques in a weight lifting exoskeleton," *J. Bionic Eng.*, vol. 16, no. 4, pp. 663–673, Jul. 2019.

[256] P. Yin, L. Yang, C. Wang, and S. Qu, "Effects of wearable power assist device on low back fatigue during repetitive lifting tasks," *Clin. Biomech.*, Vol. 70, pp. 59–65, Dec. 2019.

[257] D. J. Gonzalez and H. H. Asada, "Hybrid open-loop closed-loop control of coupled human–robot balance during assisted stance transition with extra robotic legs," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1676–1683, Apr. 2019.

[258] M. Jeong, H. Woo, and K. Kong, "A study on weight support and balance control method for assisting squat movement with a wearable robot, angel-suit," *Int. J. Control, Autom. Syst.*, vol. 18, no. 1, pp. 114–123, Jan. 2020.

[259] J. L. Samper-Escudero, A. F. Contreras-González, D. Pont-Esteban, F. J. Sáez-Sáez, M. Á. Sanchez-Urán, and M. Ferre, "Assessment of an upper limb exosuit with textile coupling," in *Proc. IEEE Int. Conf. Hum.-Mach. Syst. (ICHMS)*, Sep. 2020, pp. 1–6.

[260] D. J. Hyun, H. Lim, S. Park, and S. Nam, "Singular wire-driven series elastic actuation with force control for a Waist assistive exoskeleton, H-WEXv2," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 2, pp. 1026–1035, Apr. 2020.

[261] M. V. Pillai, L. Van Engelhoven, and H. Kazerooni, "Evaluation of a lower leg support exoskeleton on floor and below hip height panel work," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 62, no. 3, pp. 489–500, Mar. 2020.

[262] R. Flechtner, K. Lorenz, and G. Joost, "Designing a wearable soft-robotic orthosis," in *Proc. 14th Int. Conf. Tangible, Embedded, Embodied Interact.*, Feb. 2020, pp. 863–875.

[263] M. Gorsic, Y. Regmi, A. P. Johnson, B. Dai, and D. Novak, "A pilot study of varying thoracic and abdominal compression in a reconfigurable trunk exoskeleton during different activities," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 6, pp. 1585–1594, Jun. 2020.

[264] X. Ji, D. Wang, P. Li, L. Zheng, J. Sun, and X. Wu, "SIAT-WEXv2: A wearable exoskeleton for reducing lumbar load during lifting tasks," *Complexity*, vol. 2020, pp. 1–12, Nov. 2020.

[265] N. Lotti, M. Xiloyannis, G. Durandau, E. Galofaro, V. Sanguineti, L. Masia, and M. Sartori, "Adaptive model-based myoelectric control for a soft wearable arm exosuit: A new generation of wearable robot control," *IEEE Robot. Autom. Mag.*, vol. 27, no. 1, pp. 43–53, Mar. 2020.

[266] G. Ataei, R. Abedi, Y. Mohammadi, and N. Fatouraee, "Analysing the effect of wearable lift-assist vest in squat lifting task using back muscle EMG data and musculoskeletal model," *Phys. Eng. Sci. Med.*, vol. 43, no. 2, pp. 651–658, Apr. 2020.

[267] T. Poliero, M. Lazzaroni, S. Toxiri, C. Di Natali, D. G. Caldwell, and J. Ortiz, "Applicability of an active back-support exoskeleton to carrying activities," *Frontiers Robot. AI*, vol. 7, Dec. 2020, Art. no. 579963.

[268] E. S. Barjuei, D. G. Caldwell, and J. Ortiz, "Bond graph modeling and Kalman filter observer design for an industrial back-support exoskeleton," *Designs*, vol. 4, no. 4, p. 53, Dec. 2020.

[269] J. Hull, R. Turner, A. A. Simon, and A. T. Asbeck, "A novel method and exoskeletons for whole-arm gravity compensation," *IEEE Access*, vol. 8, pp. 143144–143159, 2020.

[270] L. Hao, Z. Zhao, X. Li, M. Liu, H. Yang, and Y. Sun, "A safe human–robot interactive control structure with human arm movement detection for an upper-limb wearable robot used during lifting tasks," *Int. J. Adv. Robotic Syst.*, vol. 17, no. 5, Sep. 2020, Art. no. 172988142093757.

[271] B. Treussart, F. Geffard, N. Vignais, and F. Marin, "Controlling an upper-limb exoskeleton by EMG signal while carrying unknown load," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2020, pp. 9107–9113.

[272] Z. Li, Y. Dai, J. Hu, J. Wang, and P. Tang, "Design and analysis of joint-assisted exoskeleton control system of upper limb in active spacesuit," in *Proc. 39th Chin. Control Conf. (CCC)*, Jul. 2020, pp. 3707–3712.

[273] R. Kako, N. Saito, D. Furukawa, and T. Satoh, ''Muscle activity control using an EMG feedback based pneumatic artificial muscle power-assist device,'' in *Proc. IECON 46th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2020, pp. 644–649.
[274] J. Jiang, Y. Wang, H. Cao, J. Zhu, W. Zhu, and L. Jin, ''On the control of lower extremity exoskeleton base on the interaction force of torso,'' in *Proc. Chin. Autom. Congr. (CAC)*, Nov. 2020, pp. 90–95.
[275] A. Blanco, D. Martínez, J. M. Catalán, J. V. García, S. Ezquerro, J. A. Díez, and N. M. García-Aracil, ''Oxygen consumption in industrial tasks assisted by an active upper-limb exoskeleton,'' in *Proc. 8th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Nov. 2020, pp. 576–580.
[276] M. Han, B. Shi, S. Wang, T. Li, J. Feng, and T. Ma, ''Parameter optimization and experimental analysis of passive energy storage power-assisted exoskeleton,'' *Math. Problems Eng.*, vol. 2020, pp. 1–11, Nov. 2020.
[277] J. P. Pinho, P. P. Americano, C. Taira, W. Pereira, E. Caparroz, and A. Forner-Cordero, ''Shoulder muscles electromyographic responses in automotive workers wearing a commercial exoskeleton,'' in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2020, pp. 4917–4920.
[278] P. Yin, L. Yang, S. Du, S. Qu, B. Jia, and N. Zhao, ''The effect of mobile wearable Waist assist robot on lower back pain during lifting and handling tasks,'' *Mobile Netw. Appl.*, vol. 26, no. 3, pp. 988–996, Sep. 2020.
[279] B. C. L. So, C. Hua, T. Chen, Q. Gao, and S. S. Man, ''Biomechanical assessment of a passive back-support exoskeleton during repetitive lifting and carrying: Muscle activity, kinematics, and physical capacity,'' *J. Saf. Res.*, vol. 83, pp. 210–222, Dec. 2022.
[280] O. S. Al-Dahiree, R. A. R. Ghazilla, M. O. Tokhi, H. J. Yap, and E. A. Albaadani, ''Design of a compact energy storage with rotary series elastic actuator for lumbar support exoskeleton,'' *Machines*, vol. 10, no. 7, p. 584, Jul. 2022.
[281] J. M. Li, D. D. Molinaro, A. S. King, A. Mazumdar, and A. J. Young, ''Design and validation of a cable-driven asymmetric back exosuit,'' *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1489–1502, Jun. 2022.
[282] M. Rossini, S. De Bock, V. Ducastel, K. Langlois, K. De Pauw, J. Geeroms, C. Rodriguez-Guerrero, and D. Lefeber, ''Effectiveness of a passive neck support mechanism for overhead occupational tasks,'' in *Proc. 9th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Aug. 2022, pp. 1–6.
[283] D. D. Pasqual, P. Withanachchi, G. Vimantha, R. Ranaweera, and R. Gopura, ''ArmX: An upper extremity exoskeleton robot for lift assistance,'' in *Proc. 8th Int. Conf. Control, Autom. Robot. (ICCAR)*, Apr. 2022, pp. 88–94.
[284] Y. Tu, A. Zhu, J. Song, X. Zhang, and G. Cao, ''Design and experimental evaluation of a lower-limb exoskeleton for assisting workers with motorized tuning of squat heights,'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 184–193, 2022.
[285] S. Radhakrishnan, S. Erbis, J. A. Isaacs, and S. Kamarthi, ''Novel keyword co-occurrence network-based methods to foster systematic reviews of scientific literature,'' *PLoS ONE*, vol. 12, no. 3, pp. 1–16, 2017.
[286] M. Aria and C. Cuccurullo, ''Bibliometrix : An R-tool for comprehensive science mapping analysis,'' *J. Informetrics*, vol. 11, no. 4, pp. 959–975, Nov. 2017.

S. PERERA (Member, IEEE) received the B.Sc. Eng. degree (Hons.) in mechanical engineering from the University of Moratuwa, Sri Lanka, in 2019. He was an Instructor with the Department of Mechanical Engineering and subsequently, a Lecturer with the Faculty of Engineering, University of Moratuwa. His research interests include applied mechanics, engineering design, and manufacturing with applications to robotics, aerospace, and automotive.

K. N. D. WIDANAGE (Graduate Student Member, IEEE) received the B.Sc. Eng. degree (Hons.) in mechanical engineering from the University of Moratuwa, Sri Lanka, in 2019. She was an Instructor with the Department of Mechanical Engineering and subsequently, a Lecturer with the Faculty of Engineering, University of Moratuwa. Her research interests include the industrial application of exoskeletons, biomedical applications of micro-mechanical systems, and nature-inspired robotic and control systems.

I. D. WIJEGUNAWARDANA received the B.Sc. Eng. degree (Hons.) in mechanical engineering from the University of Moratuwa, Sri Lanka, in 2019. He was an Instructor with the Department of Mechanical Engineering, University of Moratuwa, and subsequently, a Lecturer with the Faculty of Technology, University of Sri Jayewardenepura. His research interests include the industrial application of exoskeletons, biomedical applications of micro-mechanical systems, nature-inspired robotics, and control systems.

R. K. P. S. RANAWEERA (Member, IEEE) received the B.Sc. Eng. degree (Hons.) in mechanical engineering from the University of Moratuwa, Sri Lanka, in 2004, and the M.Sc. degree in computational mechanics from Swansea University, U.K., and École Centrale de Nantes, France, in 2010. He is currently pursuing the Ph.D. degree in bio-robotics with the University of Moratuwa. He has authored 40 research papers by 2022 and received several research awards both locally and internationally. He is involved in developing wearable robotic devices for medical and industrial applications with a focus on improving human–robot interaction and reducing human effort.

R. A. R. C. GOPURA (Member, IEEE) received the B.Sc. Eng. (Hons.) and M.Eng. degrees from the University of Moratuwa, Sri Lanka, and the Ph.D. degree in robotics and intelligent systems from Saga University, Japan, in 2009, with a focus on bionics and assistive robotics. He is currently a Professor with the Department of Mechanical Engineering and the Head of the Department of Medical Technology, Faculty of Medicine, University of Moratuwa. He has authored 140 research articles and obtained several patents on assistive robotic systems and wearable technology.