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Review

A Systematic Review of Occupational Shoulder Exoskeletons for Industrial Use: Mechanism Design, Actuators, Control, and Evaluation Aspects

Jin Tian [1], Baichun Wei [2], Suo Luo [3], Chifu Yang [1], Changbing Chen [4], Yingjie Liu [4], Jiadong Feng [3], Ping Li [3], Haiqi Zhu [2,*] and Chunzhi Yi [2,*]

[1] School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China; jin.tian@stu.hit.edu.cn (J.T.); cfyang@hit.edu.cn (C.Y.)
[2] School of Medicine and Health, Harbin Institute of Technology, Harbin 150001, China; bcwei@hit.edu.cn
[3] Commercial Aircraft Corporation of China Ltd., Shanghai 201323, China; luosuo@comac.cc (S.L.); fengjiadong@comac.cc (J.F.); liping2@comac.cc (P.L.)
[4] Emergency Science Research Institute, Chinese Institute of Coal Science, Beijing 100013, China; chenchangbing@mail.ccri.ccteg.cn (C.C.); liuyingjie@mail.ccri.ccteg.cn (Y.L.)
* Correspondence: haiqizhu@hit.edu.cn (H.Z.); chunzhiyi@hit.edu.cn (C.Y.)

Abstract: Prolonged awkward arm postures and repetitive tasks in industrial environments can easily lead to worker injuries. The occupational shoulder exoskeleton is a promising solution to reducing the incidence of work-related musculoskeletal disorders, especially in the shoulder. In general, the device has to be compatible with the human shoulder, which is one of the most complex joints, thus posing significant challenges in existing efforts to design occupational shoulder exoskeletons. The purpose of this paper is to present a comprehensive review of exoskeletons designed to support human shoulders and arms in industrial applications. Recent developments and advancements in mechanism design, actuators, and control aspects are discussed in detail. A brief overview of the evaluation (i.e., participants, task design, objective, and subjective assessment) is also reported, and the experiment protocol to assess performance is summarized. Finally, existing challenges and possible future research directions for occupational shoulder exoskeletons are provided.

Keywords: occupational exoskeleton; work-related musculoskeletal disorders; overhead work; mechanism design; industrial applications

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1. Introduction

Work-related musculoskeletal disorders (WRMSDs) are the primary cause of absence from work and the most common occupational disease [1]. These issues require long recovery periods, and thus reduce wage income for workers, particularly affecting people who are the primary earners in their family. For companies and society, this leads to lower productivity, heavier financial burdens, and more pressure on healthcare systems. Shoulder disorders are one of the main reasons for WRMSDs [2]. According to statistics from the United States, WRMSDs of the shoulder contribute to 13% of cases, second only to the back, but the rehabilitation period of the former is longer (23 vs. 7 days). Although the level of automation in industries is increasing, many complex tasks still require human execution, resulting in awkward shoulder postures (e.g., overhead tasks) and high physical workloads, which are strongly related to shoulder disorders [3].

Facing the increasing demand in industries, occupational shoulder exoskeletons (OSEs) have been introduced into this field. OSEs can relieve the excessive overload from users and reduce the prevalence of WRMSDs while guaranteeing work performance [4,5]. In general, OSEs have the following features: (a) torque generators to provide assistive force in the opposite direction of gravity for the target tasks; (b) physical human–machine interface (e.g., straps at the waist, arms, and chest) attached to the human body; and (c) at least one

arm bar and back bar (rigid OSEs) or Bowden cables (soft OSEs) to transmit compensating forces to the back or lower body.

In recent years, OSEs have made tremendous advances in mechanism design, actuators, and control aspects [6,7], and a number of devices have been commercialized [8,9]. However, several challenging problems remain to be solved, i.e., (a) how to maximize the flexibility and freedom of the human shoulder (i.e., kinematic compatibility) without impeding the normal motion of the human; (b) how to provide versatile assistive forces for different tasks (e.g., different heights of tasks or weights of tools); and (c) how to provide assistive forces accurately.

Recent literature reviews of occupational upper-limb exoskeletons pay special attention to their biomechanical and physiological influences, such as biomechanical modeling [10], detailed assessment framework for the occupational exoskeletons, including back, shoulder, and other exoskeletons [7,11,12], and their effects in the working environments [13,14]. In this review, we focus on providing a systematic review on mechanism design, actuators, control, and evaluation aspects of occupational shoulder exoskeletons. Compared with the review performed by Reyes et al. [5], we provide a detailed review on the assessment of the OSDs and how the assessment can form a framework to improve the design of OSDs.

The aim of this article, therefore, is to identify the real issues related to mechanism design, actuators, control, and evaluation aspects of existing OSEs. To narrow the scope of research to specific applications, the shoulder exoskeletons within full-body exoskeletons (such as the body extender [15]) or OSEs utilized for rehabilitation (e.g., CADEN-7 [16]) are not included in this study. Firstly, the methods of literature screening are introduced. Afterward, a systematic overview of the current state-of-the-art OSEs is provided, focusing on the mechanism design, actuators, control, and evaluation aspects. Finally, a comprehensive discussion and possible future directions are concluded.

2. Materials and Methods

In this paper, the literature related to "shoulder exoskeletons" published in English-language peer-reviewed journals and conferences before August 2024 was retrieved through Pubmed (MEDLINE) and Web of Science (WoS) on 31 August 2024. The Scopus database was not adopted as the document search feature was inaccessible to us. The search strategy was formulated with keywords such as "shoulder" and "exoskeleton". The same search strategy was used in the two databases, and the specified search strategy and search results can be found in Table 1. The document types of "Patent", "Dissertation Thesis", and "Review Article" were excluded from the WoS search results. In total, the search strategy outlined earlier yielded a total of 1948 (1107 + 841) initial studies, which contained 160 duplicates.

Table 1. Search strategy for databases included in this review.

Database	Search Strategy (i.e., Query Box)	Hits
Pubmed (MEDLINE)	((shoulder) OR (upper-limb) OR (upper extremity) OR (shoulder industrial) OR (shoulder ergonomic)) AND ((exosuit) OR (exoskeleton) OR (assistive device) OR (exoskeletal) OR (gravity compensation) OR (actuator)) NOT ((rehabilitation) OR (review) OR (lower limb))	1107
Web of Science	TS = ((“shoulder” OR “upper limb” OR “upper extremity” OR “shoulder industrial” OR “shoulder ergonomic”) AND (“exoskeleton” OR “exosuit” OR “assistive device” OR “actuator” OR “exoskeletal” OR “gravity compensation”) NOT (“rehabilitation” OR “review” OR “lower limb”))	841

For further screening, eligibility guidelines were established for these studies: they should (a) be exoskeletons that can support shoulder movements; and (b) focus on tasks in industrial scenarios (e.g., overhead). As a result, 86 papers remained. Nine studies from the selected papers were removed because their target tasks were not in line with the requirements, or they were theoretical research. The remaining 75 articles contained 41 different exoskeletons, and 38 out of 75 were related to evaluating the performance of exoskeletons. The complete literature selection process is illustrated in the PRISMA chart (Figure 1).

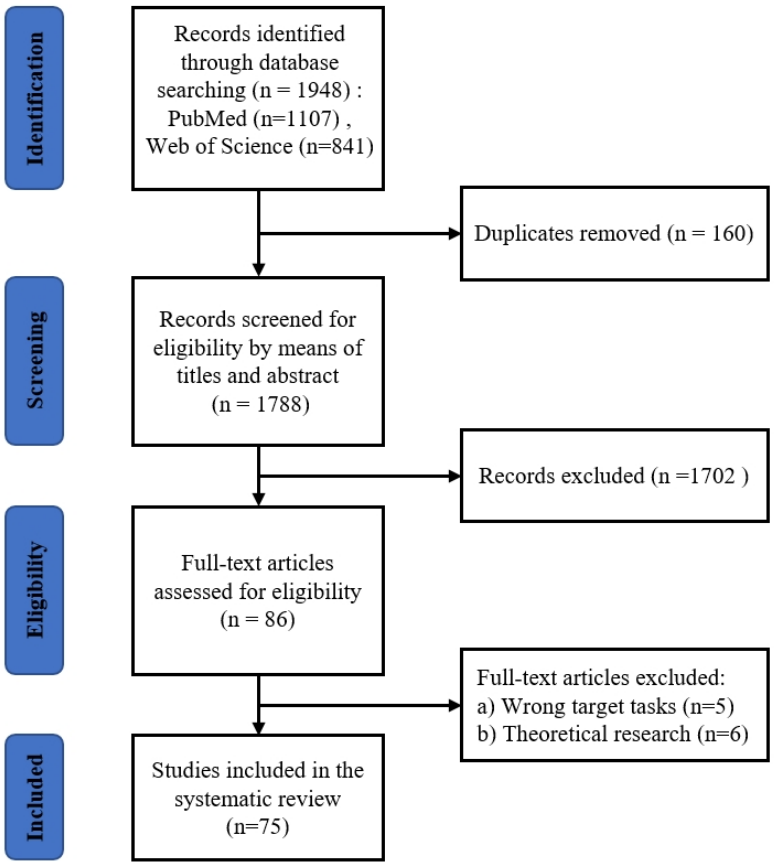


Figure 1. Selection process for research articles (n = 75) included in this systematic review (adopted from PRISMA [17]).

Summarizing these studies, it can be concluded that shoulder exoskeletons for industrial use are devices that need to meet following requirements:

(a) Sufficient range of motion (ROM): The exoskeleton provides sufficient ROM for the shoulder and arm, so as not to hinder natural human movement [18].
(b) Torque generator: The torque generator is designed such that the torque increases as the arm is raised, decreases as the arm is lowered, and does not impede normal human movement at low angles [5].
(c) Light weight and safety: Since the exoskeleton needs to be worn on the human body, it should minimize the load on humans and guarantee human safety while maintaining usability [18].
(d) Wearability: The exoskeleton should be easy to wear and remove, and the fitting size is generally adjustable to accommodate different users [18].

For a better understanding of emerging trends in OSEs, we have summarized the publication years of selected studies in Figure 2a. "Design" here refers to an article containing a description of OSEs' design, and "evaluation" here means a study that only evaluates the performance of the existing OSEs. Notably, in order to provide a more comprehensive

review of OSEs, we conducted a patent search and screened 13 patents, identifying seven different OSEs that were not included in 75 articles. As a whole, 28 out of the 48 OSEs reviewed in this paper were passive, and the rest were active (Figure 2b); 87.5% of them were rigid in structure, and the rest were soft. Particularly, among passive exoskeletons, the most popular actuator was tension springs (67.9%) in combination with other components (e.g., cable, link, cam, gear). In terms of active exoskeletons, 65% were actuated by motors, and the rest were pneumatically actuated. From the data presented above, it is most likely that passive spring-actuated OSEs or active motor-actuated OSEs will be the most popular trend in the future. Furthermore, Figure 3 shows the number of OSEs in various countries to date.

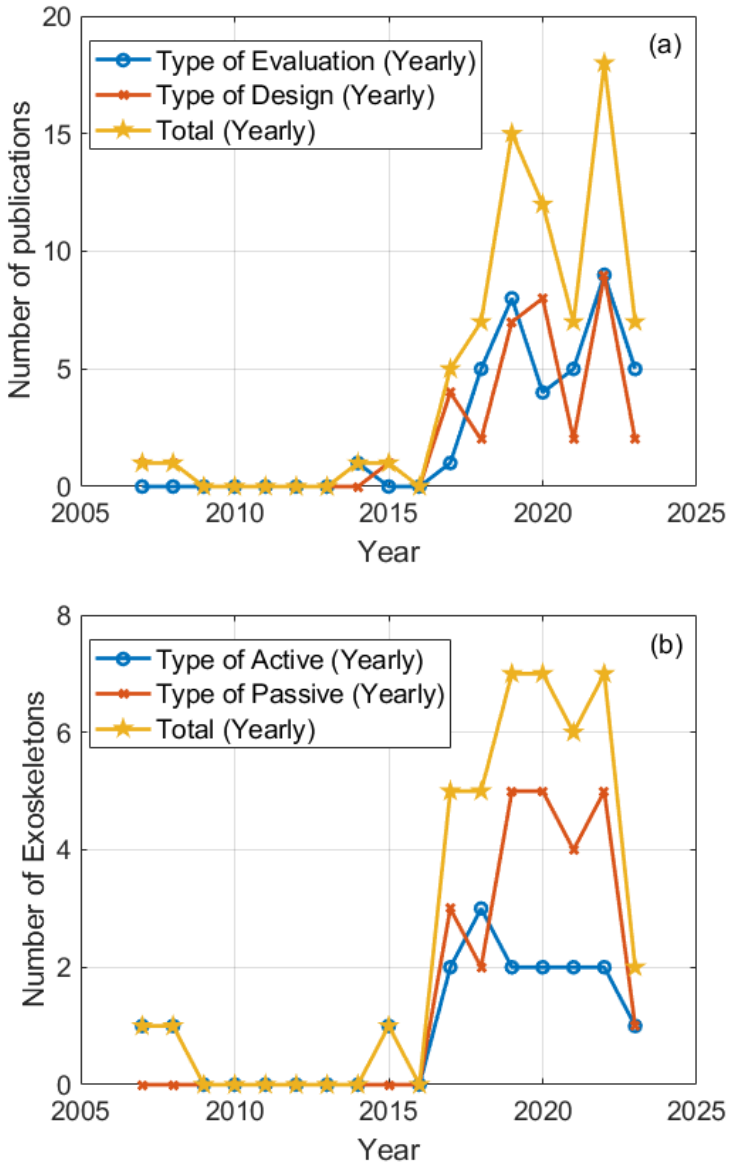


Figure 2. (**a**) Yearly and cumulative number of published articles related to shoulder exoskeletons for overhead work, categorized by design and evaluation. (**b**) Yearly and cumulative number of shoulder exoskeletons for overhead work, categorized by passive and active. "Yearly" refers to the number of the current year.

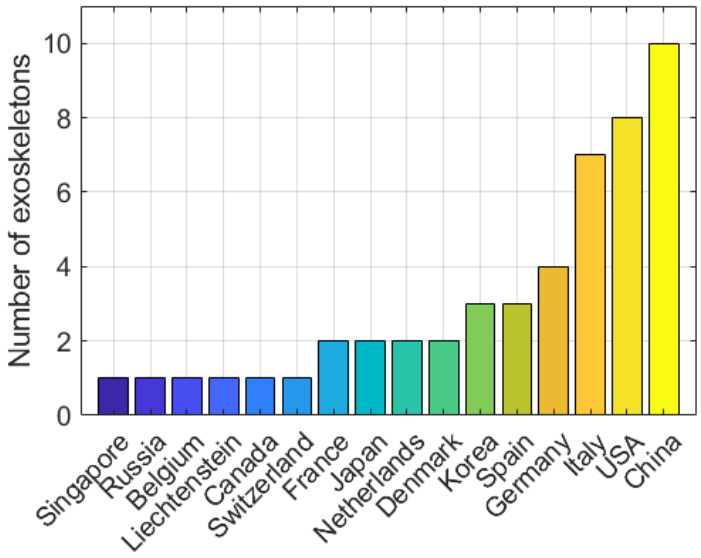


Figure 3. Bar chart of number of OSEs by country.

3. Results

3.1. Mechanical Structure Design

Understanding the biomechanics of the shoulder is essential for designing the mechanical structure of shoulder exoskeletons. For brevity, we will not repeat the review here; readers can find a detailed description in [19]. According to the materials, shoulder exoskeletons can be roughly divided into two categories, i.e., soft and rigid exoskeletons. Note that the criterion here does not incorporate the materials of actuators; only the materials of the mechanical structures are considered in this section.

3.1.1. Soft Exoskeletons

Soft exoskeletons can closely fit the human body, due to the use of the flexible materials such as elastic ropes, straps, and Bowden cables. The soft frame is usually composed of different fabrics: a stiff and non-stretchable fabric, and a strong but stretchable fabric [20]. The former is employed to fix the anchor points for fixing the force transmission materials (e.g., cables) and then transmit forces effectively. The latter is attached closely to the body to avoid undesired slides and thus enhance compliance and comfort. The Inflatable Soft Wearable Exoskeleton is a typical case, powered by a pneumatic textile actuator [21]. In fact, the soft frame often combines with pneumatic actuators or Bowden cables driven by motors, such as the Cable-Driven Shoulder Exoskeleton [22], Cable-Driven Exosuit [23], LUXBIT [24], Pneumatic Bending Actuator [25], and Wearable Soft Upper-Limb Exoskeleton [26]. In other words, soft exoskeletons are mostly active. Among the reviewed papers, only one instance, the Soft Wearable Weight Support Device (SWWSD) [27], is passive and soft, due to a combination of cams, springs, and cables.

3.1.2. Rigid Exoskeletons

Rigid exoskeletons usually have a solid back bar and arm bar connected by mechanical joints, the ROM of which mimics that of human shoulders. The back bar attaches to the user's body through a garment (e.g., belt or strap), and the arm bar is parallel to the wearer's upper arm, generating the torque in the opposite direction of gravity. Rigid exoskeletons can be categorized into two groups based on whether they consist of a mechanical joint above the human shoulder, as this is the main cause that affects a person's ROM when the exoskeleton is worn [18].

For exoskeletons with a mechanical joint above the human shoulder, they usually have two degrees of freedom (DoFs) to accommodate the flexion/extension and intra/extra

rotations of the shoulder (Figure 4), respectively, such as KSOE [18], Shoulder X [28], H-VEX [29], Two-DoF Passive Upper-Limb Exoskeleton [30], Lightweight Shoulder Exoskeleton [31], Muscle Suit [32], Hyper-Redundant Shoulder Exoskeleton [33,34], Passive Six-DoF Upper-Limb ES [35], Levitate Airframe [36], Lucy 2.0 [37], Skelex [38], EXHAUSS [39,40], UPLIFT [41,42], and DeltaSuit [43–45]. They are characterized by the adjustable sizes and levels of assistance, but their amplitudes of assistance and application scenarios are different. Overall, this type of exoskeleton can operate in narrow spaces but has a common drawback in that the device may hinder human motion at a high elevation angle of the shoulder due to unavoidable collision between the exoskeleton and the user.

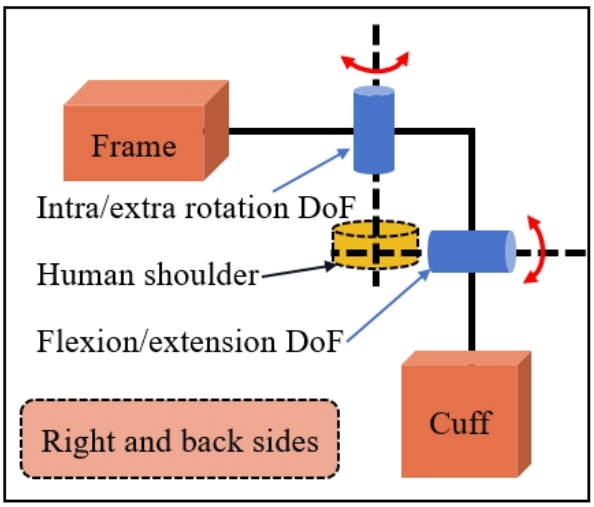


Figure 4. Diagram of the DoF chain for the OSE with a mechanical joint above the human shoulder.

Exoskeletons without a mechanical joint above the shoulder provide an alternative approach. Such exoskeletons have mainly two types: one is to shift the joint structure above the shoulder to the back, such as the MATE [46,47], Exo4Work [48], Multi-Link Shoulder Exoskeleton [49], H-PULSE [3,50], TasKi [51], ABLE [52,53], Stuttgart Exo-Jacket [54], Passive Shoulder Exoskeleton with VSM and SSM [55], AAU [56–58], Hybrid Bimanual Exoskeleton [59], Shoulder-sideWINDER [60], ULS ROBOTICS MAPS-E [61], Ekso Vest [62], ExIF [63], ExoActive EXO 18 [64–66], and Arm Assistive Exoskeleton [67], as shown in Figure 5; and the second type is to simplify the exoskeleton directly into the form of two bars connected by a hinge joint (e.g., HUST-EV [68,69], X-rise [70], CDYS [71,72], Passive Shoulder Exoskeleton [73], PAEXO [74,75], Titan Arms [76], Hilti EXO-01 [77], EVO [78], Passive Arm Assistive Exoskeleton [79], and UESTC Upper-Limb Exoskeleton [80]), as shown in Figure 6. The redundant degrees of freedom in the back of the former may lead to a larger volume, and the hinge joint of the latter may result in protrusions. Both of them can easily collide with the environment. Notably, EVO employs a stacked-link structure in the back bar, eliminating the protrusion issue [81,82].

A main consideration in mechanical structure design is to achieve alignment between the exoskeleton and human joints to achieve kinematic compatibility. As we have recognized, the problem of misalignment remains a major challenge in the design of shoulder exoskeleton structures due to the complex structure of the shoulder and the underexplored biomechanics of transmitting the assistive force through the mechanical structure. Additionally, soft and rigid exoskeletons present different characteristics. Most rigid exoskeletons can only assist with movements in the sagittal plane (i.e., shoulder flexion/extension), which generally fulfill the workspace requirements of target tasks but still suffer from a limited flexibility. Soft exoskeletons, benefiting from their soft frames, can provide assistance for the movements in the planes other than the sagittal plane. But the soft frames would induce relatively high friction and thus low transmission efficiency, which may affect the assistance.

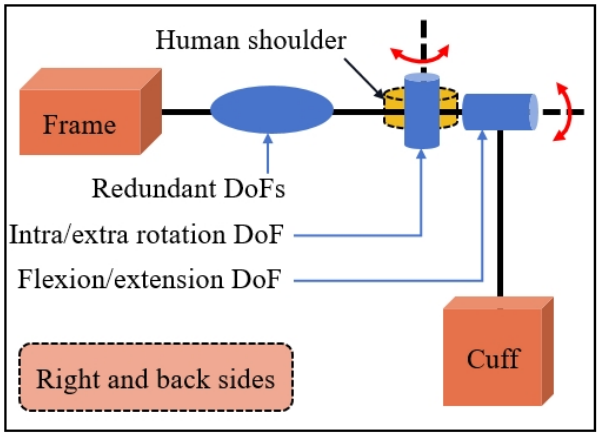


Figure 5. Diagram of the DoF chain for the OSE without a mechanical joint above the human shoulder and with redundant DoFs on the back.

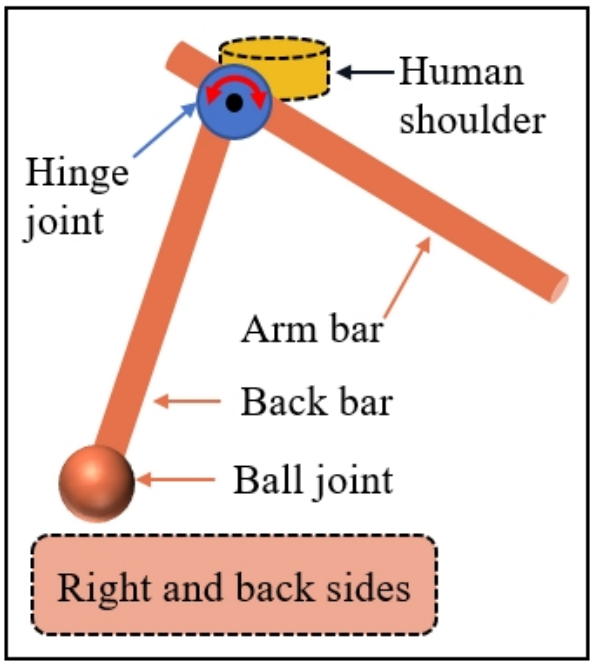


Figure 6. Diagram of the DoF chain for the OSE without a mechanical joint above the human shoulder and with an arm bar and a back bar.

3.2. Actuators and Power Systems

Actuators and power systems are fundamental components of the exoskeleton. From this perspective, exoskeletons can be categorized into three types: passive exoskeletons, whose power is derived from passive components (e.g., springs and elastic bands); active exoskeletons, in which electrical elements (e.g., motors and pneumatic muscles) are employed; and semi-passive exoskeletons, where both passive and electrical components are involved.

The assistive strategy is to generate a gradually increasing torque when the arm is raised and decreasing torque when the arm is lowered. The differences among the exoskeletons are specific implementations of torque generators. For a better review, semi-passive exoskeletons, in which the electrical components are designed to adjust the assistive level, are placed in the category of passive exoskeletons.

3.2.1. Passive Exoskeletons

Passive exoskeletons assist the body part by storing and releasing the energy of the elastic elements. The most popular elastic element is the spring, which has been used in the Ekso Vest [83,84], Levitate Airframe [85,86], etc. Table 2 lists the information of existing passive exoskeletons using different elastic elements.

Table 2. List of passive shoulder exoskeletons for industrial use.

No.	Device	Country	Structure	Weight (kg)	SAMA	Unilateral DoFs	Actuation Method	Springs Position
1	Exo4Work	Belgium	Rigid	3.8	3 Nm	6	CS	Figure 7c
2	KSOE	Korea	Rigid	3.9	10 Nm	2	TenS	Figure 7a
3	H-VEX	Korea	Rigid	2.5	10 Nm	2	TenS	Figure 7a
4	Ekso Vest	USA	Rigid	4.3	NR	4	GS	Figure 7a
5	MATE	Italy	Rigid	3.5	5 Nm	3	TenS	Figure 7a
6	Shoulder X	USA	Rigid	3.2	20 Nm	4	TenS	Figure 7a
7	Multi-Link Shoulder Exoskeleton	China	Rigid	2.0	NR	4	CS	Figure 7a
8	HUST-EV	China	Rigid	1.3	16 Nm	2	TenS	Figure 7b
9	PAEXO	Germany	Rigid	1.8	NR	2	TenS	Figure 7b
10	Titan Arms	China	Rigid	2.0	7 kgf	2	TenS	Figure 7b
11	X-Rise	Russia	Rigid	2~3	NR	2	TenS	Figure 7b
12	H-PULSE	Italy	Rigid	5.0	6 Nm	3	TenS	Figure 7a
13	EVO	USA	Rigid	4.0	15 pounds	2	TenS	Figure 7a
14	Skelex	Netherlands	Rigid	4.0	4 kg	3	LS	Figure 7d
15	Levitate Airframe	USA	Rigid	3.2	NR	2	TenS	Figure 7a
16	EXHAUSS	France	Rigid	5~6	NR	3	TenS	Figure 7a
17	CDYS	China	Rigid	2.6	NR	2	TorS	Figure 7e
18	Two-DoF Passive Upper-Limb Exoskeleton	Italy	Rigid	6.0	NR	2	PAM	–
19	Passive Shoulder Exoskeleton	Singapore	Rigid	3.2	9 Nm	2	CS	Figure 7c
20	TasKi	Japan	Rigid	NR	1.2 kgf	3	CS	Figure 7a
21	Hilti EXO-01	USA	Rigid	2.0	NR	2	TenS	Figure 7b
22	SWWSD	Korea	Soft	NR	8 Nm	–	TenS	Figure 7b
23	Passive Six-DoF Upper-Limb ES	Italy	Rigid	NR	NR	6	Elastic Band	–
24	Passive Shoulder Exoskeleton with VSM and SSM	Denmark	Rigid	2.7	2.5 Nm	3	TenS	Figure 7a
25	DeltaSuit	Switzerland	Rigid	2.0	NR	2	TenS	Figure 7a
26	UPLIFT	Canada	Rigid	NR	NR	2	TenS	Figure 7a
27	UESTC Upper-Limb Exoskeleton	China	Rigid	NR	NR	2	GS	–
28	Passive Arm Assistive Exoskeleton	China	Rigid	NR	NR	2	TenS	Figure 7b

Abbreviations: SAMA: single-arm maximum assistance; TenS: tension spring; CS: compression spring; GS: gas spring; TorS: torsion spring; LS: leaf spring; PAM: pneumatic artificial muscle; NR: not reported.

Figure 7 shows several assistive strategies of passive exoskeletons. For example, Shoulder X [87–89] and Levitate Airframe [85] employ a combination of a tension spring, a cable, and a pulley as the torque generator, located on the lateral side of upper arm (Figure 7a). A variation in pulley position can change the maximum extension length of the spring and hence the assistive torque. An example of an exoskeleton using tension

springs with links is H-VEX. It proposes a spring energy dissipation system utilizing a multi-linkage configuration and a poly-centric shoulder joint mechanism [29].

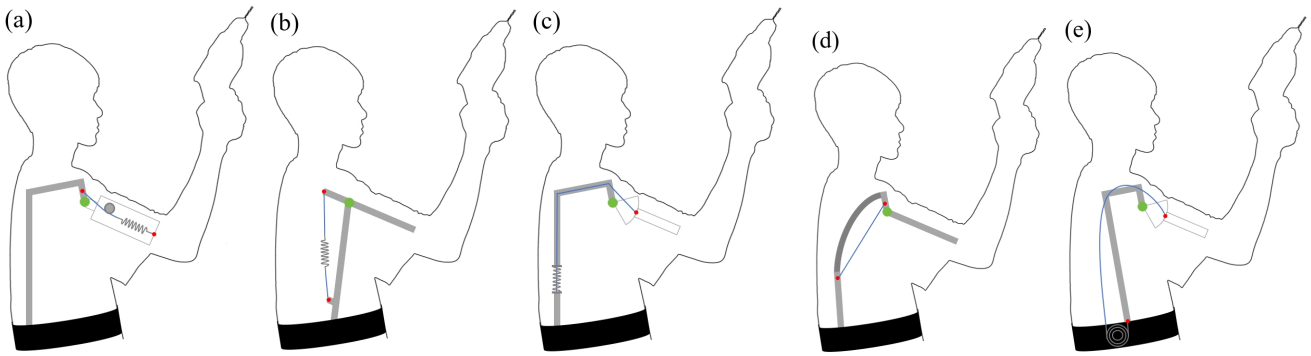


Figure 7. Summary of spring-based assistive strategies in passive exoskeletons, including a tension spring placed on the lateral side of upper arm (**a**) and back (**b**); and a compression spring (**c**), a leaf spring (**d**), and a torsion spring (**e**) placed on the back.

Additionally, shoulder exoskeletons only consisting of an arm bar and a back bar place tension springs on the back (Figure 7b, e.g., PAEXO [90], Hilti EXO-01 [77], and so on). Compression springs are also found in passive exoskeletons (Figure 7c), such as the Exo4Work [91–93] and the Multi-Link Shoulder Exoskeleton [49]. The Exo4Work places compression springs on the back and incorporates a cable and a pulley, achieving a maximum delivered torque of about 3 Nm while not impeding natural shoulder movements [91]. However, the multiple DoFs on the back of the Exo4Work induce a larger exoskeleton volume. The multi-link shoulder exoskeleton forms a cam spring energy storage mechanism located on the lateral side of the upper arm with compression spring, which avoids complex back structures, thus alleviating the aforementioned problem [49].

Leaf and torsion springs are also employed in some exoskeletons. The Skelex is a typical example of using leaf springs (Figure 7d) [38]. It replaces part of the back bar with a leaf spring and connects the arm bar and back bar with a cable. The torsion springs are found in the CDYS (Figure 7e) [71], placed on the back. Similarly, a cable connects the torsion spring to the arm bar.

As for passive exoskeletons with springs, adjusting the assistive amount by tuning the maximum deformation of springs is a common feature. Furthermore, in case the of exoskeletons that anchor springs on the back and have structures as shown in Figure 6b, they can also change the assistive amount by adjusting the length of the force arm.

3.2.2. Active Exoskeletons

Active exoskeletons employ electric components to provide power, rather than passive elements. The actuation methods of active shoulder exoskeletons for industrial use can be found in Table 3. Typical active torque generators are electric (e.g., motors) and pneumatic (e.g., pneumatic muscle) elements. Rotary motors are placed close to the shoulder, and work with multi-DoF shoulder joint structures, such as the Stuttgart Exo-Jacket [54], AAU [56], the ULS Robotics MAPS-E [61], and so on. The multi-DoF shoulder joint structures can increase the exoskeletons' flexibility, but lead to structural redundancy and heavy weight. For example, the Stuttgart Exo-Jacket has up to 12 DoFs unilaterally, and is equipped with springs to support the weight of exoskeleton arms [54]. Aiming to decrease the volume and weight of shoulder structures, some exoskeletons (e.g., the Shoulder-sideWINDER [60]) place rotary motors on the back and transmit force via Bowden cables.

Table 3. Listing of active shoulder exoskeletons for industrial use.

No.	Device	Country	Structure	Weight (kg)	SAMA	Unilateral DoFs	Actuation Method	Control Strategy
1	Lightweight Shoulder Exoskeleton	China	Rigid	2.1	NR	2	Linear motor	Force/position control
2	ABLE	France	Rigid	13.0	40 N	4	Linear motor	Force-position control
3	Stuttgart Exo-Jacket	Germany	Rigid	NR	40 Nm	4	Rotary motor	Force control
4	Muscle Suit	Japan	Rigid	4.0	NR	6	Pneumatic	Pressure control
5	Cable-Driven Shoulder Exoskeleton	USA	Soft	NR	NR	–	Pneumatic	Pressure control
6	4B-SPM Shoulder Exoskeleton	USA	Rigid	NR	NR	12	Linear motor	Position control
7	AAU	Denmark	Rigid	4.0	NR	4	Rotary motor	Force control
8	Hybrid Bimanual Exoskeleton	Italy	Rigid	6.4	NR	3	Rotary motor	Force control
9	ExIF Hyper-Redundant	Spain	Rigid	9.5	42 Nm	5	Rotary motor	NR
10	Shoulder Exoskeleton	Italy	Rigid	2.5	20 Nm	5	Rotary motor	Speed control
11	Shoulder-sideWINDER	Italy	Rigid	6.4	NR	3	Rotary motor	Force control
12	Lucy 2.0	Germany	Rigid	NR	NR	2	Pneumatic	Pressure control
13	ULS ROBOTICS MAPS-E	China	Rigid	6.5	10 kg	4	Rotary motor	Force control
14	Inflatable Soft Wearable Robot	USA	Soft	NR	NR	–	Pneumatic	Position control
15	Cable-Driven Exosuit	Spain	Soft	NR	5 Nm	–	Rotary motor	NR
16	LUXBIT	Spain	Soft	1.2	2.5 kg	–	Rotary motor and linear motor	Position control
17	Pneumatic Bending Actuator	The Netherlands	Soft	NR	4 Nm	–	Pneumatic	Pressure control
18	ExoActive EXO 18	Germany	Rigid	4.7	50N	2	Rotary motor	NR
19	Wearable Soft Upper-Limb Exoskeleton	China	Soft	NR	NR	–	Rotary motor	NR
20	Arm Assistive Exoskeleton	China	Rigid	NR	NR	2	Rotary motor	NR

Abbreviations: SAMA: single-arm maximum assistance; NR: not reported.

Another electric motor-based solution is to adopt linear motors. The ABLE employs three screw-and-cable actuators, two of which are located on the back, and one on the arm module [52,53]. The 4B-SPM shoulder exoskeleton utilizes three spherical parallel manipulators with six motors [94,95]. The exoskeleton possesses high-acceleration and fast-speed characteristics [96], but the protrusions are extremely severe, inducing a large volume. Additionally, the Lightweight Shoulder Exoskeleton consists of two spherical mechanisms with two slider crank mechanisms [31]. The equipment attaches two linear step motors to an L-shaped frame fixed on the back to drive the gravity-balancing mechanisms.

Pneumatic technology provides energy to the exoskeleton through compressed air. The Muscle Suit leverages the McKibben artificial muscle to accomplish assistance through imitating human muscle contraction [32]. One drawback is that the compressor is bulky and affects wearability. Thompson et al. drew attention to a class of soft pneumatic actuator named fiber-reinforced elastomeric enclosures, and developed a Cable-Driven Shoulder Exoskeleton [22]. The soft pneumatic actuators are placed on the back, connected to the upper arm structure using cables.

Alternatively, the pneumatic cylinder and inflatable pneumatic devices are also equipped in some exoskeletons, such as Lucy 2.0 [37] and the Inflatable Soft Wearable Robot [21]. Lucy 2.0 placed the pneumatic cylinder below the shoulder to support the upper arm bar [37]. The Inflatable Soft Wearable Robot consists of a textile-based inflatable actuator anchored to the torso and arm via a functional shirt with a non-extensible harness [21]. Similarly, the compressor of the device would affect wearability.

3.3. Control Strategies

Control strategies of exoskeletons relate to the implementation of active assistance. In general, passive exoskeletons do not involve control strategies; instead, they tune the assistive level by means of replacing the elastic element or reconfiguring the mechanical structure. As for semi-passive and active exoskeletons, their control strategies can be categorized into physical and manual signal-based control strategies according to the input signals.

3.3.1. Physical Signal-Based Control Strategies

Physical signal-based control strategies employ signals generated outside the human body, such as force, position, and pressure. Such control strategies rely on sensing the information of the human–machine interaction [56] from force sensors that measure human–exoskeleton interactive forces, or IMUs enabling estimation of joint angles, or pressure sensors to obtain the pressures of compressed air. Information on control strategies for active exoskeletons can be found in Table 3.

Some physical signal-based control strategies utilize force controllers to control the interactive force between the exoskeleton and the user, such as the Lightweight Shoulder Exoskeleton [31], Hybrid Bimanual Exoskeleton [59], ULS ROBOTICS MAPS-E [61], AAU [58], ABLE [52], Stuttgart Exo-Jacket [54], and the Shoulder-sideWINDER [60]. Here, we report several typical instances. The force controller of the AUU obtains the desired angular velocity by the measured interaction forces and admittance filter [58]. Then, the PI controller tracks the desired angle velocity and computes the assistive force. The ABLE has realized force feedback control without force sensors due to the advantages of the screw-and-cable actuators [52]. The Stuttgart Exo-Jacket includes two-level controllers for each motor [54]. The high-level controller calculates the reference torque using the signals measured by IMUs and force sensors and then sends them to the low-level controller. And the low-level controller utilizes the interaction force to perform the torque control and gravity compensation.

Alternatively, some physical signal-based control strategies use position controllers to explicitly drive the exoskeletons in a pre-determined trajectory, such as the 4B-SPM Shoulder Exoskeleton [94], LUXBIT [24], the Inflatable Soft Wearable Robot [21], and the Hyper-Redundant Shoulder Exoskeleton [33]. The 4B-SPM shoulder exoskeleton obtains the forward and inverse kinematics of the 4B-SPM based on the user's desired position, to obtain a new position, which is sent to the position controller [96]. LUXBIT collects the kinematic data via flexion sensors and calculates the difference with the reference position, which is fed to a sliding mode controller [24]. The Inflatable Soft Wearable Robot designs a kinematics-based controller that implements an IMU kinematic estimator to obtain the shoulder angle and angular velocity. Then, state machines are used to transition between the inflated and deflated states [21].

In addition, the pressure controller is also implemented in physical signal-based control strategies of exoskeletons (e.g., the Muscle Suit [32], Cable-Driven Shoulder Exoskeleton [22], and Lucy 2.0 [37]). The Muscle Suit achieves the pressure control by regulating the compressed air. The Cable-Driven Shoulder Exoskeleton and Lucy 2.0 will be reported subsequently for their involvement of manual regulation-based control strategies.

3.3.2. Manual Signal-Based Control Strategies

Manual adjustment relates to manually inputting a reference value for the control variable via an external device (e.g., a rotary knob, button, or joystick). For example, the Hyper-Redundant Shoulder Exoskeleton adjusts the reference speed of the robot using an external joystick, and then employs the PID speed controller to perform the speed control and to flex and extend the user's arms [33]. The Cable-Driven Shoulder Exoskeleton controls the air pressure in the pneumatic actuator with a manual regulator and a digital pressure gauge [22]. Lucy 2.0 applies three types of information to obtain the desired pressure of the pneumatic cylinder, including the rotary knob located at the shoulder strap, the remote push button mounted on the grip of the tool, and the elevation angle of the upper arm measured by a flat linear potentiometer [37]. Lucy 2.0 then applies the pressure control (a type of physical signal-based control strategy) to generate the assistive torque. Lucy 2.0 can be treated as a classical representative of hybrid control strategies that combine the manual signal and the physical signal-based control strategies.

3.4. Evaluation

A preliminary evaluation plays an important role before the exoskeleton is adopted in real application scenarios. The aim of the evaluation is to assess the usability of exoskeletons in terms of ROM, work efficiency, fatigue levels, and acceptance of users. In this section, several crucial elements of the evaluation are presented, including the participants, task design, and evaluation indicators. In total, 38 articles evaluating OSEs are summarized and reported here, among which 11 were conducted in the field and the others in a laboratory setting. The primary goal of this section is to provide interested researchers with a valuable reference for the evaluation of OSEs, where information can be accessed directly and easily.

3.4.1. Participant Characteristics

The participants recruited in the reviewed literature have the following common characteristics: (a) Individuals had not experienced shoulder-related pain recently. (b) Individuals had never worn the exoskeleton before. (c) In the laboratory setting, individuals had no prior experience with the target tasks, whereas in the field setting, individuals were experienced with the target tasks. Among these studies, 48.6% considered the effect of gender balance. In total, 608 participants (SA = 32.4 y $\pm$ 5.7, SH = 174.8 cm $\pm$ 13.2, SW = 76.7 kg $\pm$ 8.8) were recruited and the average ratio of male with respect to female participants was 2.4:1 (no gender was mentioned for 194 participants). In addition, 29% of the reviewed evaluation papers recruited experienced workers to perform the tasks (SC = 222, SA = 37.3 y $\pm$ 6.1, SH = 176.5 cm $\pm$ 13.3, SW = 84.4 kg $\pm$ 9.2), and the rest of the studies recruited participants with no work experience (SC = 386, SA = 29.9 y $\pm$ 5.5, SH = 173.9 cm $\pm$ 13.2, SW = 72.6 kg $\pm$ 8.5).

3.4.2. Task Design

For the task design, tasks can mainly be classified into two categories: static tasks and dynamic tasks. Not all studies involved static tasks, but all of them involved dynamic tasks. The top six dynamic tasks are screwing, drilling, connecting wires, lowering and lifting, tracing lines, and assembly tasks. Their distributions are shown in Figure 8. Out of 38 shoulder exoskeleton evaluation studies, 14 studies included the drilling task: four for a simulation of the real drilling task (holding a tool to push the ceiling and controlling the pushing force within a predefined value), four for drilling tasks with different work heights, four for real drilling tasks with a fixed height, and two for drilling tasks with different tool weights. Screwing, included in eight studies, was another prevalent task in valuating OSEs, usually found in automobile assembly lines. The following categories are lowering and lifting, and assembly tasks. Additionally, the tasks of connecting wires and tracing lines were used to evaluate the potential benefit of OSEs during a precision task.

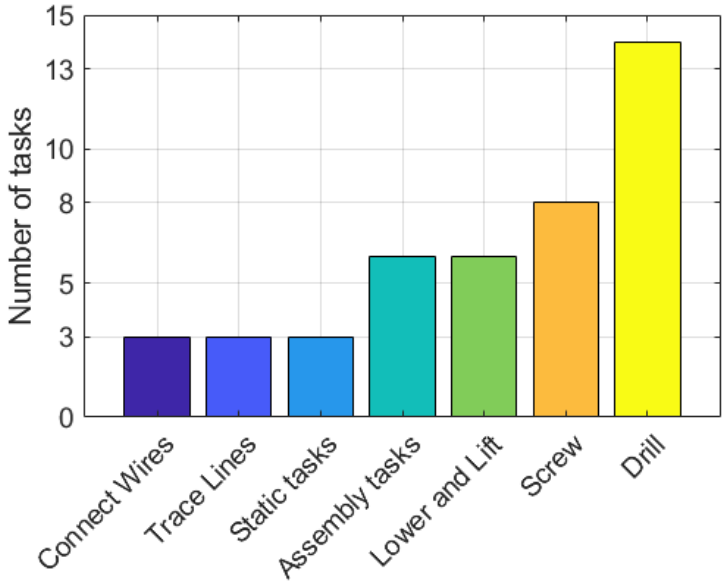


Figure 8. Bar chart of number of tasks.

3.4.3. Objective Evaluation Indicators

To evaluate the effectiveness of OSEs, objective evaluation indicators (OEIs) are needed as a criterion. They can be categorized into physiological and physical OEIs. Within the physiological OEIs, EMG-related indicators were the most commonly reported (91%), including normalized EMGs, mean power frequency, and so on, in order to observe variations in muscle activation when assisted by OSEs. The counts of muscles involved in the reported studies were 163, containing 36 categories of muscles. And the reported muscles and their numbers are listed in Figure 9. The anterior deltoid (AD), medial deltoid (MD), and posterior deltoid (PD) are agonist muscles to keep the arm raised, and are expected to directly benefit from the OSEs. The biceps brachii (BB) and triceps brachii (TB) are the elbow and shoulder flexor and extensor, respectively [97]. The latissimus dorsi (LD) is an antagonist muscle for assessing how the lower arms work against the resistance from the OSEs. The erector spinae (ES) was chosen to assess if loads shifted from the shoulders and arms to the lower back [97].

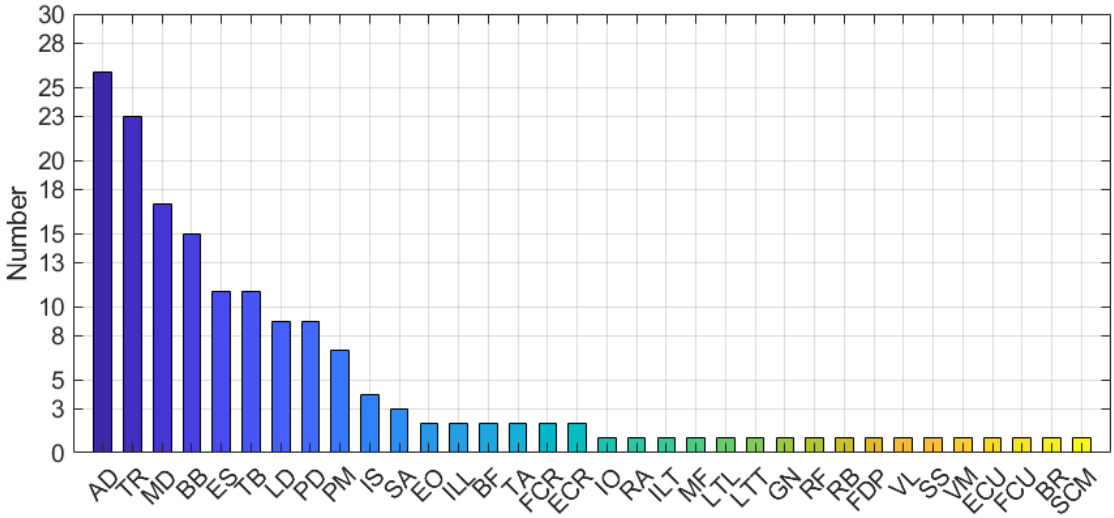


Figure 9. Reported muscles and their numbers. AD: anterior deltoid; TR: trapezius; MD: medial deltoid; BB: biceps brachii; ES: erector spinae; TB: triceps brachii; LD: latissimus dorsi; PD: posterior deltoid; PM: pectoralis major; SA: serratus anterior; IS: infraspinatus; EO: external oblique; ILL: iliocostalis lumborum pars lumborum; BF: biceps femoris; TA: tibialis anterior; FCR: fexor carpi

radialis; ECR: extensor carpi radialis; IO: internal oblique; RA: rectus abdominis; ILT: iliocostalis lumborum pars thoracis; MF: multifidus; LTL: longissimus thoracis pars lumborum; LTT: longissimus thoracis pars thoracis; GN: gastrocnemius; RF: rectus femoris; RB: rhomboids; FDP: flexor digitorum profundus; VL: vastus lateralis; SS: supraspinatus; VM: vastus medialis; ECU: extensor carpi ulnar; FCU: fexor carpi ulnar; BR: brachioradialis; SCM: sternocleidomastoid.

As for the physical OEIs, joint angles, torque (44%), and task durations (31%) were frequently used to assess the ROM and working efficacy of users. And the third popular indicator was the center of pressure (19%), which can be used to determine whether an exoskeleton affects body balance and working posture.

3.4.4. Subjective Evaluation Indicators

Out of 38 articles evaluating OSEs, 26 studies included 44 subjective evaluation indicators (SEIs). The rating of perceived discomfort (RPD), ratings of perceived exertion (RPE), and the system usability scale (SUS) were found to be the mostly used SEIs. Overall, the percentages of RPD, RPE, and SUS are 27.3%, 40.9%, and 27.3%, respectively. The Borg CR-10, Borg CR6-20, NASA-TLX, and TAM were typically used to assess RPE. As for RPD, the frequently mentioned body parts were the upper arm, low back, shoulder, forearm, and waist. In general, the RPE scales should be conducted after every task, the RPD scales should be conducted when all tasks within one condition were completed, and the SUS scales should be conducted after the exoskeleton was worn [98]. The relationship between task and condition can be found in Figure 10.

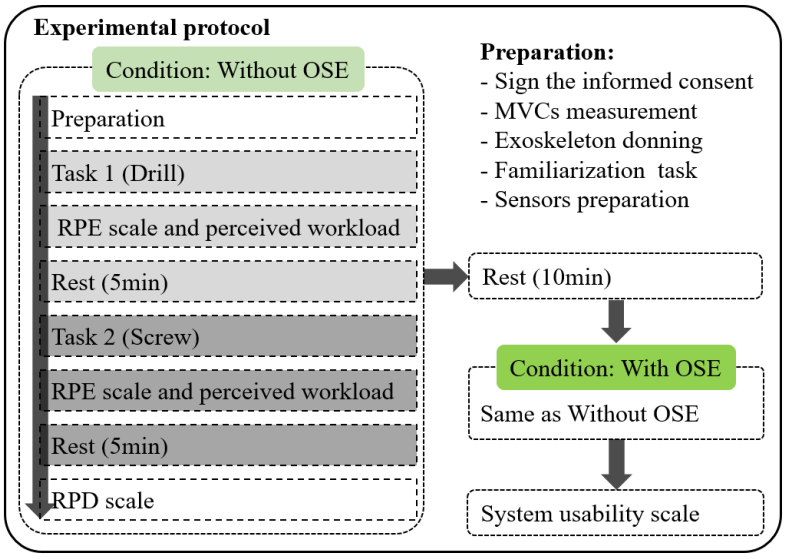


Figure 10. Experimental protocol of evaluating OSEs.

4. Discussion and Future Direction

In this systematic review, we reported the information on mechanical structure design, actuators and power systems, control strategies, and evaluation of OSEs. Although significant progress has been made in many aspects of the OSEs, there are still several issues to be addressed before they are available in a large-scale field application. In this section, we will discuss the remaining challenges and their possible future directions.

4.1. Mechanical Structure Design

In terms of mechanical structure design, rigid mechanisms are more commonly used in OSEs. Currently, most commercially available products are made of rigid elements. To summarize from the reviewed studies, the rigid shoulder exoskeletons have the follow-

ing advantages compared to soft ones. First, they are more durable, which is a critical characteristic for consumers. Second, they can provide more powerful assistance and load carrying capacity due to the relatively large force arms with respect to the shoulders. Third, they can facilitate more precise force transmission and offer enhanced safety and stability. Nevertheless, there are certain obstacles hindering their widespread adoption.

To begin with, the lack of kinematic compatibility between the exoskeleton and human [48] would affect wearability. The misalignment induced by the issue may impede the user's natural movement and thus induce discomfort and pain. The shoulder joint is one of the most flexible joints in the human body, and its rotational center is variable [99]. While numerous research organizations have attempted various solutions, such as the design of a joint structure above the shoulder [18], multiple-DoF mechanical joints [100], and two-bar (back and arm) mechanisms [75], they all underperformed in one or more aspects of compactness, weight, and flexibility. In the future, considerations may include the design of reconfigurable shoulder joint structures, or the integration of biomechanical optimization for the shoulder joint structure.

Additionally, the rigid shoulder exoskeleton (passive or active) should have a small volume and light weight, while enabling functional efficiency. A heavy device would increase the physical workload of users and requirements of actuators [29]. A large volume would increase the possibility of collisions, thus impairing its practicability in field applications. This issue should be considered concurrently with alleviating joint misalignment, which may employ complex mechanical structures, thus increasing the possibility of the former problem. Predominantly used rigid materials are carbon fiber composites and aluminum alloys. With advancements in material science, new materials with low density but high stiffness may be applied in the future. Prior to that, a compact, simple, and aligned shoulder joint structure remains the primary research focus.

Lastly, another bottleneck preventing their wide applications is the displacement of the physical human–machine interface (pHMId). The pHMId can lead to an increase in interaction forces, causing discomfort and making it less suitable for prolonged usage [46]. Most shoulder exoskeletons are secured to the body through straps or cuffs around the waist, arms, and/or chest, which results in relatively poor stability while working. An attachment scheme with two or multiple anchor points should be studied in the future for a better user experience.

In comparison to their rigid counterparts, soft shoulder exoskeletons have several positive aspects, such as being smaller and lighter, having lower inertia, and so on. However, they also have the intrinsic drawback of textile-based frames. They might provide less stability, especially when precise movements or posture control is required. In addition, they may still cause discomfort or fatigue during prolonged usage due to the shear force on human body interfaces [5]. Moreover, flexible materials may wear out faster and require more frequent maintenance or replacement compared to rigid components. And some advanced flexible materials could be expensive to manufacture and maintain. In general, there is still a considerable journey ahead before the widespread deployment of flexible exoskeletons in practical applications.

4.2. Actuators and Power Systems

In terms of passive OSEs, they are more affordable and lightweight, and can provide a balance between effectiveness and wearability. Several exoskeletons among them have been commercialized [101], though mostly for a specific target task. But some disadvantages have been introduced with the use of elastic elements. The direction of the generated assistive force by elastic parts is always opposite to gravity, and hence the antagonistic muscles work against the assistance when lowering the arms, which may result in discomfort and increased muscle effort. Additionally, the hysteresis characteristics of the springs may lead to a higher force than expected when the arms are lowered [91]. The springs serve as low-pass filters, which limit the torque control bandwidth, posing another inherent drawback. Finally, the assistive timing is critical. That is, the assistive force would be more

efficient when it peaks at the peak angle of the target task. Existing passive devices mostly have a single assistive timing; thus, they are not suitable for multiple tasks with different work heights and tool weights. Moreover, determining the optimum level of the assistance remains an open question.

Active shoulder exoskeletons have the ability to generate versatile torque profiles, utilizing sensors and electric actuators. But they are generally more expensive, heavier, and bulkier, which may limit their widespread field applications. Specifically, the most dominant actuating approaches are electric and pneumatic. The electric elements (e.g., motors) are prone to breakdown in high-temperature and dusty environments, which easily occurs in industrial production lines. And the pneumatic actuators have difficulty in precise force control and stroke length [5].

To our knowledge, the force would transfer but not magically disappear. Whether it is active or passive, the force generated by OSEs transfers the load of shoulders to other parts of the human body. How to achieve functional efficiency without adding additional strain to other parts is a long-term consideration that exoskeletons will need to address in the future.

4.3. Control Strategies

Control strategies relate to how the assistive strategies can be implemented by the active exoskeletons, and can reflect the design principle of the assistive strategies. Human–exoskeleton interactive information usually serves as feedback for the control loop. The ultimate target is to assist humans with exoskeletons in a compliant, precise, and timely manner.

Physical signal-based control strategies are popular in OSEs due to the availability of cheaper sensors and stable signals. The physical signals are used to determine the motion states of the users and then estimate the level of assistance. To determine the users' motion states, the main challenge is to perform the estimation in a timely manner. Physical signals are generated along with human movement, which could lead to a lag in assistance due to the transmission delay of the mechanical structures. The prevalent approach nowadays is based on kinematic or interaction force information. In the future, the fusion estimation strategy of multiple physical information may achieve better performance to compensate for the intrinsic deficiencies of physical signals.

For estimating the level of the assistance, the primary obstacle is the principle of determining the optimum assistance. The presence of system uncertainty and the demands of different tasks can contribute to different levels of assistance, which will make it difficult to estimate the assistive force. Similarly, it is difficult to perform the estimation accurately using only single-modal information, and multi-modal fusion will be the main solution in the future.

Compared with physical signal-based control strategies, physiological signal-based control strategies, which utilize bioelectric signals (e.g., electromyography, electroencephalography, etc.) as feedback, have not been reported in OSDs for industrial use. Possibly, it is due to signal instability and limitations of signal acquisition equipment in industrial settings. For instance, the cost of sensors, sweat during operations, and signal noise are all not conducive to industrial applications. However, the greatest advantage of physiological signals is their ability to anticipate physical actions [102], allowing for the detection of a person's motion intention in advance, and they have shown remarkable effectiveness in the field of medical rehabilitation [103,104]. In the future, advances in computer science may improve their stability. And the authors believe that physiological signal-based control strategies, while currently more investigated at a mechanistic level, are poised for further development.

The manual regulation-based control strategies are more consistent with human assistance intent, safer, and more accurate, with user engagement through rotary knobs, buttons, and joysticks. However, this approach is not very efficient, has a low level of automation, and is prone to human operational errors. From the perspective of technical

implementation, the challenges include combining manual regulation with the automatic detection of human intent, and utilizing human intelligence without overly interrupting the users.

4.4. Evaluation

For the evaluation of OSEs, there is currently no standardized evaluation process [105,106]. We hope to provide a relatively standardized evaluation process for reference. Thus, based on what we reported earlier with regards to evaluation, we have summarized the evaluation experimental protocol (Figure 8). The "familiarization task" in the preparation phase includes familiarizing the target tasks, the exoskeletons, and the subjective scale (e.g., the Borg CR-10 scale). Generally, the participants are asked to perform a "wall sit" to the limit of their endurance while providing scores of RPE at the thighs using the selected scale [76]. In Figure 8, we list two tasks (drilling and screwing), two conditions (with or without OSE), and two reference duration of rest between trails and sessions, all of which can be adjusted by specific requirements.

The OSEs involved in the field evaluations are EksoVest [107,108], EVO [81], the Levitate Airframe [109,110], Shoulder X [101,111,112], MATE [47,100,113], PAEXO [101,114], Skelex [98,115], and Hilti EXO-01 [77], which are already commercially available. In laboratory settings, most participants had no prior experience with the target tasks, which is different from field tasks, which were characterized by noisy, crowded, and dirty environments. Consequently, these evaluations may generate different outcomes with experienced workers and field tasks. More convincing results would be achieved if they could be evaluated in a standard field setting. A common problem for both settings is that they are all conducted in a single task, not a set of tasks. A set of tasks in a real work scenario contains actions other than the target tasks (e.g., a combination of changing tools, bending, walking, and turning) [5].

Moreover, most evaluation studies are conducted within a single day, which overlooks the long-term effects of work and fatigue; thus, this may derive different results in terms of comfort, productivity, and other potential effects. To the authors' knowledge, at the time of writing, only one research had been conducted with an 18-month field study employing the EksoVest for automotive assembly [108]. Overall, in the future, evaluations should be directed toward real work scenarios, a full set of tasks involved in field, and long-term effects.

5. Conclusions

This systematic review has reported the state-of-the-art in the design, control, and evaluation of occupational shoulder exoskeletons. The OSEs that assist with overhead work during industrial tasks have positive effects on reducing the activation of the corresponding muscles, improving work efficiency, and thus mitigating the risk of WRMSDs. Currently, commercially available OSDs are mainly passive and rigid OSEs, favored for their simplicity, affordability, and stability; however, they are limited to single tasks and often suffer from significant misalignment between users and the rigid structures. Soft and active OSEs, which have potentially better wearability and flexibility, are under extensive investigation to optimize the weight, cost, actuator type and position, and assistive strategies. Moreover, most assistive strategies of existing OSEs are only aimed at counteracting arm gravity. A higher level of assistance that can work for lifting much heavier objects can be further investigated. As for the evaluation aspect, we argue that a standardized and systematic evaluation can be essential for optimizing the performance of OSDs, which should consider objective factors, subjective factors, and long-term effects. The review aims to facilitate the further development of occupational shoulder exoskeletons.

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preparation, S.L., J.T. and C.Y. (Chunzhi Yi); writing—review and editing, J.F., P.L., J.T. and C.Y. (Chunzhi Yi); visualization, J.T.; supervision, C.Y. (Chifu Yang) and C.Y. (Chunzhi Yi); project administration, J.F. and P.L.; funding acquisition, C.Y. (Chunzhi Yi). All authors have read and agreed to the published version of the manuscript.

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