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ASSESSMENTS AND EVALUATION METHODS FOR UPPER LIMB EXOSKELETON - A LITERATURE SURVEY

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ABSTRACT

Exoskeleton technology has gained great interest in several fields including robotics, medicine, rehabilitation, ergonomics, and military. Especially, upper-limb exoskeletons are developed aiming to increase worker's physical ability such as stability, force and power production and reduce biomechanical loads, working fatigue, which relieves overexertion risk. Extensive research has been conducted to assess existing and newly proposed exoskeletons, but they still have trade-offs and user convenience issues to resolve. Therefore, the primary purpose of this paper is to review classification of the upper-limb exoskeletons and functional assessment, particularly regarding the complex interactions between human and exoskeleton. Secondly the paper is to provide insight in issues associated with the upper-limb exoskeletons. Finally, discussion on future directions for upper limb exoskeleton development and assessment is presented.

Keywords: Passive exoskeletons; upper limb; assessment; musculoskeletal disorders

1. INTRODUCTION

Exoskeleton is an external frame that can be worn to enhance human physical performance. American society for testing and materials (ASTM) defined exoskeleton as a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity [1]. The exoskeleton can be applied to military, medical, industrial, public safety and consumer/recreational fields, and its terminologies have been evolving following the improvement of the exoskeleton technologies. According to the most recent U.S. Bureau of Labor Statistics (BLS) [2] "By Musculoskeletal Disorders (MSDs)" category, there were a total of 266,530 cases of musculoskeletal disorders by nature reported by all private industries in the Year of 2019 and a median of days away from work at 13 days. Particularly, 83,500 cases were in the upper extremity areas, second only to the trunk injuries at 121,220 cases, and a median of days away from work at 19 days. From the Work Foundation Alliance, more than 44 million people in the Europe suffer from the musculoskeletal disorders, and the total annual cost for the European economy exceed €240 billion [3]. Even in 2019, EU-OSHA (European Agency for Safety and Health at Work) reported that millions of workers were affected by MSDs, and MSDs incurred billions of euros to employers [4]. Exoskeleton has been suggested as one of the solutions for the difficult-to-automate situations in the workplace [5]. Particularly, upper-limb exoskeletons, much resembling an robotic arm, have been utilized in a variety of fields, for example, improving working performance in industrial field [6], rehabilitation in the medical field [7], assisting disabled people in activities of daily living [8], and carrying heavy loads in military field [9].

The first exoskeleton, named Hardiman, was developed by General Electronics in the 1960s [10]. It is a whole-body exoskeleton consisting of powered arms and legs to amplify human power. It was activated using the master-slave system with hydrolytic actuators. However, its usage was limited due to its large size and heavy weight. Later, exoskeletons could be operated without a master-slave system because of newly proposing method called physical human-robot interaction (pHRI) [11]. Upper-limb exoskeletons have been in the spotlight in the biomedical and engineering sectors, with manufacturing companies that operate production lines and actively engaging in development. For example, automobile companies such as Hyundai, Chrysler, etc. [12], [13] are investing in the exoskeleton development, in addition to providing exoskeleton testing environments. Bogue [14] reported the general trend of exoskeleton development. Following the exoskeleton development, which was led by the military and medical fields, the use of exoskeleton is in the spotlight in the manufacturing industry. The Europe and the Far East companies have been making endeavor in this market to become the forefront position.

Previous literature reviews mainly focused on summarizing the models of exoskeletons and their evaluation methods. Several researchers warned about the overestimation of benefits and underestimate risks associated with use of exoskeletons. The present review focuses on the following steps. The upper-limb exoskeletons are first categorized, and then the assessments of the exoskeletons are summarized. Next, the issues based on assessment results are analyzed. Finally, current problems on the upper limb exoskeletons and the future direction are briefly discussed**.**

2. METHODOLOGY

This section describes a series of methods used to search for the literature from the database and classify the elected literature. materials and methods that have been used in the work must be stated clearly.

2.1 Literature survey process

A systematic literature survey process was conducted through three steps: Keyword selection, Search in free database (Google Scholar), and Filtering. The papers in this review preferred to be published in the same field journals, and then screened from books, conference papers, and technical reports. Commercial exoskeletons were considered as the priority for this review, and the on-process and research aimed at exoskeletons came next.

Terms used in bibliographical searches included exoskeleton, industry, trade-off, interaction, and upper limb / upper extremity. The database search query was composed of three concepts: commercial upper limb exoskeletons, interaction between exoskeleton and human body, and assessment of upper extremity exoskeletons. Additional studies were screened from a free search and from reference lists of database articles and related reviews. 38 articles focused on evaluating the upper-limb exoskeletons, and 17 of them were proposing new prototypes and models. 9 articles were review papers and they reviewed the categorization and application of exoskeletons.

2.2 Categorization of the exoskeleton

Based on the areas of human body supported, the exoskeletons are classified into 3 types, upper-limb, lower-limb, and full-body exoskeletons. For the upper-limb exoskeletons, they have been further categorized in the literature according to several factors, including applied limb segment, degrees of freedom, actuator type, power transmission method, joints, applications, etc. From the viewpoint of the powering mechanisms, the exoskeletons can be divided into active and passive exoskeletons. Gopura et al. [15], and Gopura & Kiguchi [16] reviewed active upper-limb exoskeletons and classified them in three groups according to the actuator types: electric motor, pneumatic power, and hydraulic power actuated systems. Each actuator type has pros and cons, shown in Table 1. Improved from the traditional 3 types, series elastic actuators (SEA), variable stiffness actuators (VSA), and pneumatic actuators are popularly applied to the exoskeleton systems. SEA and VSA showed enhanced performance in term of human-robot interaction by regulating interaction forces, avoiding rigidly moving subjects' limbs [17]. Otherwise, passive ones tend to use levers, springs, and other non-electrical systems to support the human body. Fox et al. (2019) divided the exoskeletons into eight types according to the utility in the industry: grabbing, sitting, lifting arms, etc. They compared the enhancement and the restriction of each type of exoskeleton. Although there have been many other classification methods, most of the occupational exoskeletons are passive, so researchers have focused on developing and improving the passive exoskeletons. Interestingly, a semi-passive upper-limb exoskeleton was recently proposed by Grazi et al. [19] who suggested this in-between category that uses low-power actuation units to improve the behavior of the spring-based actuation. The main purpose of semi-passive exoskeleton is making the active exoskeleton less bulky and heavy.

From the point of current industrial use, the upper-limb exoskeletons can be divided into two groups: motion amplification and medical rehabilitation [20]. Earlier research and development of exoskeletons was focusing on the military and rehabilitation fields. Recently there was a shifting of interest to occupational applications such as in manufacturing industries. Zhu et al. [21] categorized the industrial exoskeletons based on exoskeleton types, functions, and assessment procedures. Because of the large differences in performance requirements, few researchers developed exoskeletons that overlap these application fields.

TABLE 1: FEATURES OF THREE ACUTATOR TYPES USED IN ACTIVE EXOSKELETON

Actuator type	Pros	Cons
Hydraulic	· High horsepower-to-weight ratio · Safety from the automated system	· Relatively expensive in initial investment · High cost for the maintenance

		· Possibility of oil leakage
Pneumatic	· Fast cycle speed, high productivity · Lower cost than hydraulic and electric actuators · Simple structure	· Limited amo nt of power u · Short life span · Performance issues with high and low temperature (ai -water content) r
Electric	· Effective for quick and light work · Accurate work performance · Less potential risk of pollution	· Low cost-effectiveness · Higher risk of break own bec u e of complex structure d a s

In this review paper, commercially available exoskeletons are classified into three types. The first type is a power glove which reduces the amount of force an operator needs to hold a tool during a task. Iron hand from GOBIO is a commercially available power glove (Fig. 1a). Power gloves only amplify the grabbing power. It does not augment human capability for dexterous work.

The second type is the representative and most popular type of upper-limb exoskeleton that supports the arms and shoulders. This type of exoskeleton employs human body support by transferring the weight of arms, shoulders, neck, and upper back to the human body's core musculature. Robo-mate, EksoEvo, ShoulderX (Fig.1b) and Steadicam Fawcett Exovest are the commercially available ones. Additionally, many researchers have been proposing new exoskeletons to reinforce shoulders/arms. The main profit of this type is reducing shoulder muscle forces and maximum joint angles, thus capable of decreasing risk of repetitive work-related MSDs.

(a) (b) (c)

FIGURE 1: FOUR TYPES OF EXOSKELETONS: (a) power glove [22], (b) exoskeleton for arms/shoulders, (c) gravity balancing exoskeleton

The third type is gravity balancing exoskeletons, for example, EksoZeroG series from Ekso Bionics and Exopush from RB3D (Fig. 1c). These exoskeletons can provide assistance when lifting heavy tools by transferring the load onto the external supporting base such as floor. The EksoZeroG series are robotic arms at one end that seize heavy tools and the other side is linked to the other type of exoskeletons. The evaluation of the EksoZeroG series in combination with the second exoskeleton types has been reported by several researchers [23]–[26]. Exopush is used when the workers need additional thrust force such as using an asphalt rake.

Table 2 shows the commercially available upper-limb exoskeletons following the classification methods commented above. The dominant number of exoskeletons are passive exoskeletons for arms/shoulders, and they are designed to combine into lower-limb exoskeletons / back supporting exoskeletons according to the working environment.

TABLE 2: CLASSIFICATION OF COMMERCIAL UPPER-LIMB EXOSKELETONS INTO 3 TYPES: 1) POWER GLOVE, 2) EXOSKELETON FOR ARMS/SHOULDERS, AND 3) GRAVITY BALANCING EXOSKELETON

Model name	Company	Actuation	Type
Airframe	Levitate	Passive	2
Armor-man 3.0	Tiltamax	Passive	2
Best G	yber Human C Systems	Passive	2
C DYS	Crimson Dynamics Technology	s Pas ive	2
Eksopush	Ekso Bionics	Passive	3
EksoZeroG	Ekso Bionics	Passive	3
Exy One	Linha Industrial	Passive	2
Fawcett Exovest	Steadicam	Passive	2
Fortis	Lockheed Martin	Passive	2,3
H-VEX	Hundai	Passive	2
Ironhand	BIOSERVO	Active	1
LIGHT'	HMT	Passive	2
MATE-XT	COMAU	Passive	2
Muscle Upper	INNOPHYS	Passive	2
Paexo	Ottobock	Passive	2
PLUM'	HMT	Passive	2
Power Assist Glove	Gloria Mundi Care	Active	1
Shiva Exo	Ergo Sante	Passive	2
ShoulderX	SuitX	Passive	2
Skel'Ex	Skel'Ex	Passive	2
V22	StrongArm Tech	Passive	2

Wieldy	Beijing Wieldy CES	Passive	2
X-Rise	ExoRise	Passive	2

3. HUMAN-EXOSKELETON INTERACTION ASSESSMENT

This section introduces the existing assessments of exoskeletons and points out the issues of human-exoskeleton interaction. The first two subsections highlight the primary obstacles which are critical to use in industrial environment, and the third subsection proposes popular assessment articles of upper-limb exoskeletons. The advantages and disadvantages expressed in each article are briefly summarized.

3.1 Increased loading on the lumbar spine

The effectiveness of upper-limb exoskeletons, such as decreasing shoulder muscle efforts, rating of perceived exertion and discomfort, has been well documented [27]. In this review, we are rather interested in interactions of exoskeletons with human body and the potential injury risks. Only few researchers focused on the trade-off of the upper-limb exoskeleton, particularly the biomechanical loading to the low back [24]. In Weston's experiment, the Steadicam Fawcett Exoskeletal vest is combined with the zeroG2 & zeroG4 to represent an upper-limb exoskeleton with the zeroG2 as the mechanical arm. The spinal load including compression, anteroposterior shear and lateral shear and peak and mean muscle forces were evaluated. The study showed that wearing the exoskeleton led to higher spinal joint loads and muscle activities than without wearing it. Especially, the compressive spinal load and torso extensor muscle activity were increased up to 56%. While these results might not be extrapolated to other exoskeletons, researchers who are developing new exoskeletons should consider this important trade-off as cautioned by the authors.

3.2 Misalignment between the exoskeleton and human body

Many researchers have been trying to propose optimized designs for the discrepancy between the rotational axis of mechanical and anatomical joints, but it was difficult to support the natural human motion using the external frame. If the exoskeleton cannot predict human movement correctly, the inappropriate direction and torque can be applied to the human body. This is particularly an issue for the shoulder joint as its motion is the most complex in the body. Several exoskeleton vests such as MATE (Comau), Airframe (Levitate) and EksoVest (EksoBionics) tried to solve this issue by including redundant degrees of freedom (DOF) around the scapula. For example, Hyun et al. [28] proposed a poly-centric structure to resolve this issue, and Bongsu Kim & Ashish D. Deshpande [7] developed 5-DOF shoulder joint considering the wide range of motion (ROM). Shoulder joint cannot be described simply by 3 DOF spherical motion contemplating only the Glenohumeral (GH) joint. Sternoclavicular (SC) joint and Acromioclavicular (AC) joint are also known as collaboratively cooperate with GH joint to maximize the shoulder ROM, so several exoskeletons are trying to cover the mobility of shoulder girdle: either elevation-depression or protraction-retraction.

Sylla et al. [29] proposed a prediction method in terms of neuromuscular mechanisms. They applied hybrid cost function to decrease the joint torques and got a good alignment between the predicted trajectory and the measured one. They concluded that the new model was effective for the prediction, but more investigations are needed for long-term effect of experiments with longer testing period.

3.3 Outcomes of individual exoskeleton assessment

In this part, 9 different types of exoskeleton assessments have been reviewed (Table 3). Relatively popular and recently developed exoskeletons are selected, and these assessments are representative references of newly proposing exoskeletons. Table 3 shows the brief impacts of exoskeletons, and the subsections (3.3.1 ~ 3.3.9) explain the detailed testing environment, working motion and affected muscles.

TABLE 3: ASSESSMENTS OF UPPER-LIMB EXOSKELETON FOR ARMS/SHOULDERS

Exoskeletons	Assessment from related studies	References
Eksovest	· Decreasing the task completion time · Reducing shoulder abduction range	[6,30,31]
Exhauss stronger	· Reducing the shoulder flexor muscles · Increasing the triceps brachii muscle activity	[32]
Shoulder X	· Reducing the peak loading and increasing median loading on the shoulder · Decreasing the shoulder muscle activity	[26,37]
WADE	· Effective with overhead work with the load (over 3.4kg) · Trade-off: increased loading on the lumbar spine	[24,25]
Airframe	· Increased painting productivity · Trade-off: increased loading on the lumbar spine	[33,38,39]
Robo-mate	· Reducing the medial deltoid and biceps brachii muscle activation	[34,40,41]
PAEXO	· Decreasing the metabolic parameters with overhead tasks	[35]
H-Vex	· Improving the ROM and muscle activity	[28]

V22	· Improving the ROM and muscle activity	[36]

3.3.1 Eksovest

EksoVest is a passive upper limb exoskeleton developed by Ekso-BIONICS. The most recent model is EksoEvo which increases durability and decreases the weight of the exoskeleton. Kim et al. [6], [30] have evaluated the performance of EksoVest with the overhead drilling task as shown in Fig. 2 (a). The results showed that the task completion time decreased 3.4 seconds (18.9%) and the shoulder abduction range of motion reduced up to 10%. However, the number of errors increased in the drilling task. The potential reason could be the speed-accuracy trade-off, extremity proprioception, and requirement of long training period for the adoption. Recently, Weston et al. [31] tested Eksovest and other exoskeletons and reported the similar enhancements.

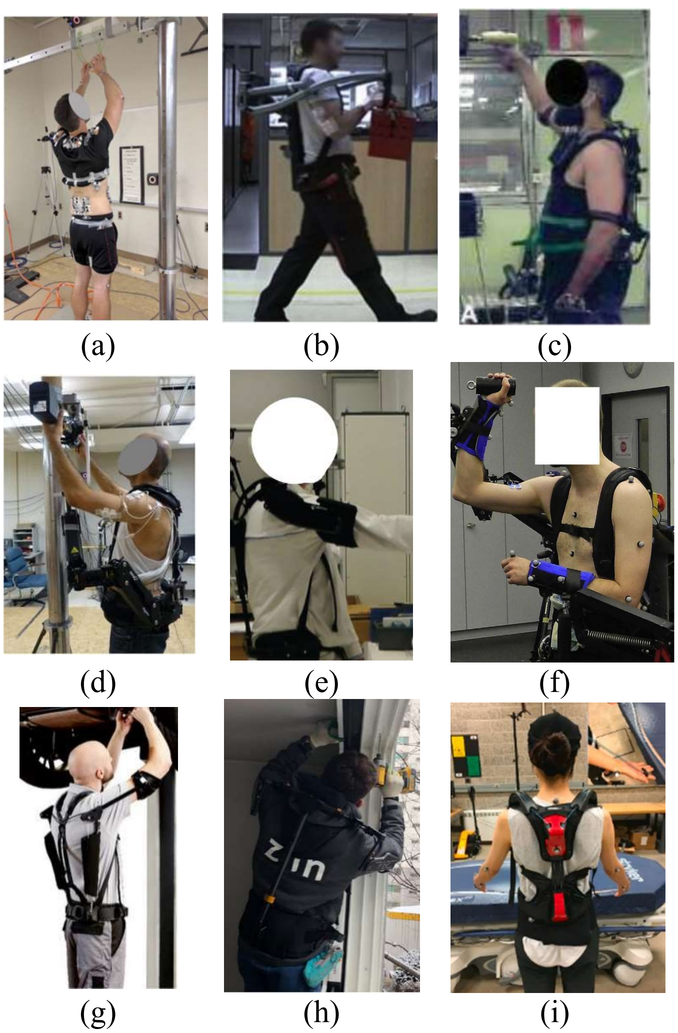

FIGURE 2: ASSESSMENTS OF SIX COMMERCIAL UPPER-LIMB EXOSKELETONS: (a) EksoVest [30], (b) Exhauss Stronger [32], (c) ShoulderX [32], (d) WADE [32], (e) Airframe [33], (f) Robo-mate [34], (g) PAEXO [35], (h) H-VEX [28], and (i) V22 [36]

3.3.2 Exhauss Stronger

As shown in Fig. 2 (b), Theurel et al. [32] evaluated an upper limb exoskeleton named Exhauss Stronger. They reported that wearing the exoskeleton was beneficial by reducing the workload of shoulder flexor muscles in the load lifting and lowering task and the boxes staking/unstacking task; for example, the EMG activity of the anterior deltoid muscles decreased up to 50%. On the other hand, there was a significant increase in muscle activity at the triceps brachii when carrying out the tasks. In addition, the use of Exhauss Stronger did not produce significant effect on the perceived efforts on the shoulder during the lifting and stacking tasks.

3.3.3 ShoulderX

Alabdulkarim and Nussbaum [26] and Pinho et al. [37] evaluated the ShoulderX by SUITX in a laboratory environment. Alabdulkarim and Nussbaum [26] compared three different exoskeletons: the FORTIS by Lockheed Martin that is a full-body exoskeleton, the ShoulderX as the upper-limb exoskeleton, and the Steadicam Fawcett Exovest with the zeroG2 that is an upper-limb exoskeleton with a mechanical arm. They tested overhead drilling and analyzed three physical factors: maximum acceptable frequency (MAF), ratings of perceived discomfort (RPD) and muscular loading. The results showed that the exoskeletons reduced the peak loading on the shoulder but increased the median loading. However, the participants felt low back discomfort with use of the upper limb exoskeletons, and the frequent movements of the upper arm straps caused discomfort to them. One of the interesting parts from their assessment was that they compared the MAF between genders, and the result showed that female and male have totally different trends with different exoskeletons. For example, with the full-body exoskeleton, males showed similar MAF compared to without the exoskeleton, but females showed lower MAF. This result implies that workers should choose optimized exoskeleton in their working environment.

Pinho et al. [37] compared three different upper limb exoskeletons: ShoulderX (Fig.2c), Mate by Comau and Paexo by Ottobock. They tested three different drilling tasks which are overhead, shoulder flexion at 90° and shoulder flexion under 90 °. Especially, the test was conducted at the factory environment with assembly line workers. The results showed that all exoskeletons decreased shoulder muscle activities. Among the three exoskeletons, the Paexo had the best performance, but not significantly different from the others. The authors commented that there was no effect of amplifying or damping the tool vibrations with the exoskeletons. It was more dependent on the task and the tool types.

3.3.4 Steadicam Fawcett Exovest – wearable assistive device (WADE)

The Steadicam Exovest designed by Chris Fawcett is a semi-rigid exoskeletal vest originally intended to transfer the weight and torque of the Steadicam camera support system to anatomically appropriate areas without interfering with natural movement. When replacing the camera support with a robotic arm such as ZeroG2, the vest can be used for other purposes. Rashedi et al. [25] used the mechanic arm (zeroG2) with the exoskeleton and tested overhead work, which involved keeping a tool engaged with a hexagonal bolt as shown in Fig. 2d. They reported that using the mechanical arm and the WADE appeared effective at the overhead task when the load was heavier than 3.4 kg. However, the authors also found that the female subjects enrolled in the study could not complete the experimental protocol, suggesting that future work including both genders is warranted.

Weston et al. [24] also tested the WADE with a mechanical arm (zeroG2 & zeroG4). They reported the biomechanical risk to the shoulders from handling heavy tools can be mitigated by using the exoskeleton. However, they also reported the trade-off of the exoskeleton on spinal joint load discussed above in Section 3.1.

3.3.5 Airframe

The Airframe exoskeleton is a product from Levitate Technology. Butler [38] reported that with Airframe one painter's productivity improved by 26.79% and the other by 53.13% while performing a dynamitic, repetitive job. He concluded that the welders and painters might benefit from use of the exoskeleton due to reduced level of fatigue as fatigue is considered as a risk to the workers.

Fig. 2e shows one of the evaluations by Spada et al. [33], in which they assessed 3 tasks with Fiat Chrysler Automobile (FCA) workers wearing Airframe. First, they tested maintaining a static upright standing posture with extended arms while holding a load (3.5kg). Then, they analyzed the repeated manual material handling tasks with participants moving a load between two positions of different heights. The last task was a precision task, in which participants traced a continuous wavy line on a paper fixed on a billboard. The authors reported that the workers increased their performance by 30% in average when wearing the Airframe.

Gillette and Stephenson [39] evaluated shoulder and trunk muscle activities in use of Airframe. The EMG values showed an average 25% reduction in the deltoid, biceps, and spinae muscles when wearing Airframe. However, the effects on the trapezius were mixed. The authors suggested a possible shoulder strap restriction of scapular elevation as the reason behind the observations.

3.3.6 Robo-mate

The Robo-mate exoskeletons have three configurations: passive arms, active arms, and active trunks. Huysamen et al. [34], [40] assessed the three-segment, passive arm from Robo-mate and found that the back segment weighed 2.8kg and two arm attachments weighed 4.1kg each. The participants lifted a 2 kg load to the overhead height as shown in Fig. 2f. The results showed that the medial deltoid and biceps brachii muscle activities reduced by 62% and 49% respectively, and perceived arm effort by 41%. However, the exoskeleton did not affect the trunk and leg muscle activities significantly. Otten et al. [41] evaluated a prototype of Robo-mate with three tasks: fastening object above head level, setting screws above head level, and grinding at the wall. They reported that the provided support not only reduce anterior deltoid activity but also reduce latissimus dorsi activity.

3.3.7 PAEXO

The PAEXO exoskeletons are made by Ottobock from Germany. To appraise this exoskeleton, Schmalz et al. [35] tested two overhead tasks: screwing nuts and drilling. The experiment investigated the biomechanical and metabolic effects of PAEXO under controlled condition. With metabolic parameters, the measured O2 and heart rate decreased 33% and 19%, respectively. They concluded the working activities are less fatiguing overall with PAEXO. With biomechanical parameters, the kinematics showed no significant difference between with and without condition. On the contrary, the deltoid and biceps brachii muscles presented drastically decreased EMG.

3.3.8 H-Vex

The robotics team of Hyundai motor company introduced a novel passive type upper arm exoskeletal vest [28]. They proposed 2 important mechanical structural elements. Firstly, they added an energy-storage multi-linkage mechanism to dissipate loaded energy according to angle-increment of a wearer's upper arm. Secondly, they applied 4-bar poly-centric linkage for the misalignment issue of upper-limb exoskeletons. The result showed both improvement in the ROM and muscle activity. Their next goal is providing manual phase adjustment of the torque.

3.3.9 V22 ErgoSkeleton

The V22 is the upper-limb exoskeleton produced by StrongArm Technologies. It is composed of passive-back support and arm assistive systems. Hwang et al. [36] compared three exoskeletons: FLx, V22 and Laevo. They tested the patient transfer task which contains squat pivot, stand pivot and scoot. Although V22 showed decreased shoulder muscle activities (anterior and middle deltoid), the effectiveness was small (mean difference: 1.6 and 4.1%, respectively), and the right middle deltoid showed increased MVC with the scoot motion.

4. DISCUSSION AND CONCLUSION

4.1 Assessment methods

Howard et al. [42] have commented that developing appropriate consent safety standards for the safe use of wearable exoskeletons is demanded. They suggested that ISO 13482, which is the safe design regulation for wearable robots, would be suitable for the exoskeletons. Additionally, ASTM International has already published two standards for exoskeletons: F3323 on terminology and F3358 on labeling and other informational requirements. Nevertheless, there has been no clear standard for evaluating the exoskeletons [27], [42]. Previous researchers have managed the force myograph (FMG) and EMG signals to obtain the force and torque experienced by the subjects when using exoskeletons. Several researchers also utilized the ratings of perceived discomfort (RPD) and perceived exertion (RPE) to assess the exoskeletons.

Recently, ASTM published new standards of ergonomic parameters with respect to exoskeletons: F3474-20, F3518-21, F3443-20, etc. They are considering the appropriate safety, health, and environmental practices and the applicability of regulatory limitations prior to use. However, still the maintainability, training, device certification has been issued from the past standards. It implies that we should consider both device and user's sides to give confidence for buyers.

4.2 Potential virtual assessment through digital human modeling (DHM)

DHM method is a technology that describes human scale, proportions, and musculoskeletal attributes which emerged as a design methodology helping human modeling and simulation [43]. Demirel stated that the terminology, DHM, may have more than one meaning following the connotation and nuances of different fields. In the study, commercial software was categorized into four groups based on the application domain, and researchers who have developed the exoskeletons utilized those models for design and analysis of dynamic processes as well as of static and anthropometric processes. Maurya et al. [44] also mentioned the potential power of DHM method for improving work environment, and P. M. Kuber & Rashedi [45] presented that software like Jack, CATIA, RAMSIS and Creo is beneficial for the performance measurement, reach-capability check and visibility check. Several researchers applied multibody dynamics software (Anybody, OpenSim) to predict the unmeasured values and simulate its dynamic interactions [46]–[49].

4.3 Overestimation of exoskeleton benefits

Many development and assessment articles emphasize the advantage of exoskeletons, for example, exoskeletons are beneficial to reduce muscle fatigue and joint loads. But researchers should also investigate the disadvantage or unexpected results of exoskeleton for future work. Picchiotti et al. [50] reported an interesting result related to the two posture assistive exoskeletons: FLx and V22. They reported that there was no significant biomechanical benefit on the spinal loads. Especially, the compression, anteroposterior shear, and lateral shear forces with and without the exoskeletons were less than previously expected. Similarly, Schmalz et al. [35] showed that there was no compelling difference of joint angles wearing exoskeletons. Therefore, future assessment should contain the advantages on one side and the unanticipated results from the other sides.

4.4 Design standards

Commercially available exoskeletons are not unified into one design method, so every upper limb part is designed with a different number of DOF. With the upper limb, the joints have been divided into 3 main parts: shoulder, elbow, and wrist. Shoulder movement has been described as 3 or more DOF joints, based on shoulder GH joint and its girdle movements. Elbow joint have modeled as the 1-DOF revolute joint in the most development articles, but some of the applications made it 2-DOF considering the forearm supination /pronation. The complex movements between the radial and ulna bones caused the different design strategies, and the wrist is commonly assumed to be a 2-DOF revolute joint. Therefore, further research is recommended to clearly compare the advantages and disadvantages of increasing DOF on each joint, because the efficiency of DOF increasement is not defined following the working environment.

4.5 Conclusions

The objective of this paper is to summarize and discuss the categorization, assessment of exoskeletons and primary findings. Since manufacturing companies are pursuing improving working environment by use of the upper-limb exoskeletons, many studies have been conducted to develop an impact design. The evaluation of commercial upper-limb exoskeletons was summarized to figure out the knowledge gaps in this field. The review shows that the most exoskeleton studies demonstrated reduced fatigue in upper extremity muscles, thus were effective on working performance. However, our review points out that there can be exceptional or unexpected issues with the use of exoskeletons. The assessment studies are recommended to contemplate not only the main objectives, but also the overall points in the process, particularly from body areas where the load is transferred to through the exoskeleton. Additionally, the discomfort from use of exoskeletons, for example, the friction and the misalignment between the exoskeleton and human body, should be included in the assessment with quantification values or levels.

Though many studies have been proposing different adjustment methods by increasing high DOF on the shoulder or remaining extra length for the end-users, it is obvious that building an optimized structure for each user has remained a difficult issue. To relieve this issue, DHM has been applied to consider both the working environment and human-exoskeleton interaction. Previous studies tried to import the simplified exoskeleton to the software and obtained simulated values. Future studies need to embody the working motion and elaborate exoskeleton prototypes on the software to evaluate the working performance. After designing prototypes, an impact guideline is requested to cover the device durability, efficiency, and user training courses. We encourage new researchers who design a new exoskeleton to refer to this review, and actively advance the commercial products to enhance working environments.

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