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Developments in hardware systems of active upper-limb exoskeleton robots: A review

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HIGHLIGHTS

- Reviews developments of active upper-limb exoskeleton robots.
- Presents major developments of exoskeleton hardware systems occurred in history.
- Identifies major research challenges in exoskeleton robots.
- Provides a classification, a comparison and a design overview of mechanisms and actuation.
- Presents future directions in upper-limb exoskeleton robots.

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ABSTRACT

The very first application of active exoskeleton robot was to provide external power to a soldier so that he can carry additional weight than his strength. Since then this technology has focused on developing systems for assisting and augmenting human power. Later this technology is expanded into other applications such as limb rehabilitation and tele-operations. Exoskeleton research is still a growing area and demands multi-disciplinary approaches in solving complex technical issues. In this paper, the developments of active upper-limb exoskeleton robots are reviewed. This paper presents the major developments occurred in the history, the key milestones during the evolution and major research challenges in the present day context of hardware systems of upper-limb exoskeleton robots. Moreover, the paper provides a classification, a comparison and a design overview of mechanisms, actuation and power transmission of most of the upper-limb exoskeleton robots that have been found in the literature. A brief review on the control methods of upper-limb exoskeleton robots is also presented. At the end, a discussion on the future directions of the upper-limb exoskeleton robots was included.

1. Introduction

UPPER-limb robotic devices can broadly be divided into two types: prosthesis and orthosis. Prosthesis is an artificial substitute that one can wear in place of a missing body part. Orthosis is an orthopedic apparatus that can be used to support and correct deformities of a person or to improve functionality of movable parts of the body [1]. The orthoses can further be divided into two major types: devices that are made to align the end effector with the user, and devices that are designed so that the device joints are made to be aligned with the joints of the user [2]. The former type of orthosis is external to the human body and it provides required force to move the end of the user's limb (palm, in case of upper-limb) to a desired position [3–7] without considering individual joint motions of the upper-limb [8]. The latter type of orthosis is referred to as the exoskeleton robots and it is generally worn by the human beings. The joints and links of the robot have direct correspondence with the human joints and limbs respectively, and robot axes are expected to be aligned with the anatomical axes of the upper limb. Exoskeleton robots are widely researched in the areas related to rehabilitation [9–14], assistive robotics [15–20], human power augmentation [21], impairment evaluation [2], resistance exercises [22] and haptic interaction in tele-operated and virtual environments [18,23]. Assistive robotics and robotic rehabilitation are becoming increasingly important as potential technologies to

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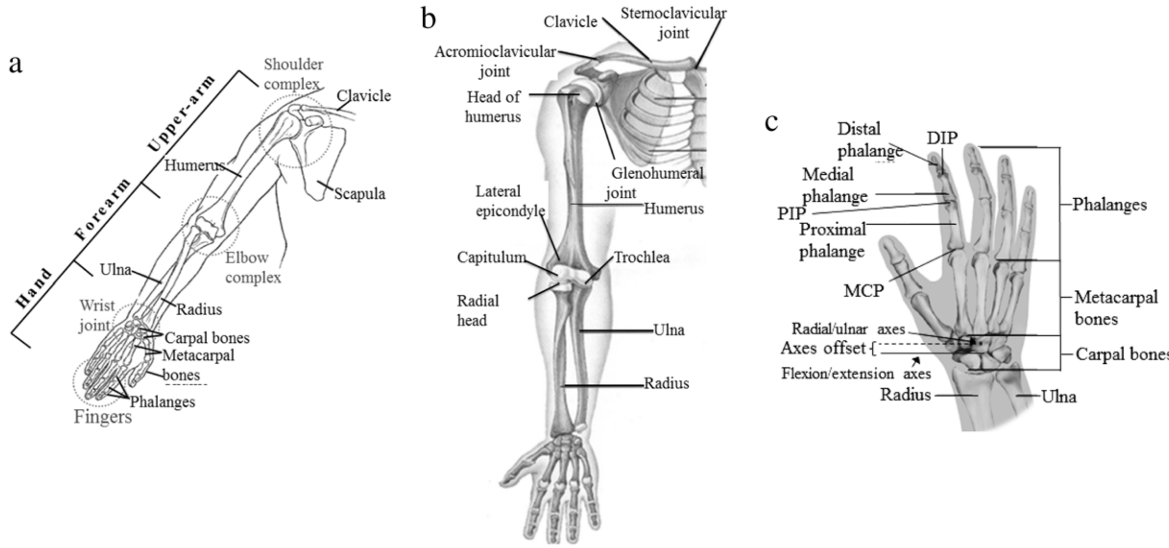

Fig. 1. Anatomy of human upper-limb. (a) Upper-limb segments. (b) Shoulder and elbow. (c) Wrist and hand.

assist physically weak elderly population. Therefore, exoskeleton robots can be used to improve the quality of life of individuals who requires external assistance for their daily activities.

Even though the concept of exoskeletons was formulated in 1883, very first exoskeleton robot was designed in 1936 [24,25]. Then "Hardiman" was developed in 1961 with the objective of augmenting power of human. Hardiman was a whole body exoskeleton robot and it was actuated by several hydraulic actuators [26]. A human was placed inside the robotic system and the Hardiman augments the whole body motion of the operator. Vukobratović et al., proposed three lower-limb exoskeleton robots from 1969 to 1973 [27]. However, the real development of upper-limb exoskeleton robot was first appeared in 1990 and was developed in the University of Minnesota with the objective of increasing the limb strength of the human [28,29]. The complexity of the upper-limb exoskeletons has been increased significantly and currently these systems have evolved into assisting much complex shoulder movements [15,30]. Throughout the history many upper-limb exoskeleton robotic systems have been proposed for rehabilitation, and/or power-assist of physically weak individuals, haptic interaction, and human-power augmentation [9–21,23,30–112].

Analysis of the mechanical design of the robots is a crucial element in the construction of an effective exoskeleton robotic system. During the last few years several review papers appeared in the literature, particularly for assistive and rehabilitation applications. Review articles are available covering the full spectrum of the body including upper and lower limb robots [3,70,113–123]. The recent reviews suggested that there has been a significant growth of upper-limb exoskeleton robots occurred in the last decade [123]. A comprehensive review of the upper-limb robots is therefore useful in view of designing such systems for exoskeleton robots as suggested in [36].

Interaction between wearer and the exoskeleton robot is twofold: physical human–robot interaction (pHRI) and cognitive human–robot interaction (cHRI). pHRI can be used to identify the suitability of exoskeleton system [24]. cHRI is the other aspect which takes intelligence into account for the control of the robot [24]. In order to provide comfort and safety to the wearer during manipulation with the exoskeleton robot, pHRI has a more significant role and different aspects such as actuation, power transmission, dexterity, DOF, singularity, kinematic chain and compliance [124]. Therefore, in this paper, the major developments in hardware systems of active upper-limb exoskeleton robots are synthesized by considering pHRI. In this paper we have excluded the hand exoskeleton as the literature available on hand exoskeleton robots are as extensive as upper-limb exoskeleton robots. In Section 2, we explain the upper-limb anatomy that helps to understand hardware designs of upper-limb exoskeleton robots. The major developments in the history are presented in Section 3. Section 4 presents the major research challenges encountered in upper-limb exoskeleton robots at present. Furthermore, we provide a classification of upper limb exoskeleton robots in Section 5. The classification can be based on five different criteria: method of actuation, location of application of the body, power transmission method, application domain, Degrees of Freedom (DOF), and control method. Each classified robot is compared based on its mechanical specifications. Design overview of the mechanism, actuation and the power transmission of most of the upper-limb exoskeleton robots found in the literature is presented. Several key projects undertaken by major research centres are included in Section 6. A brief review on the control methods of upper-limb exoskeleton robots is also presented in Section 7. Final section of the paper devotes to the discussion and the future direction of research in upper-limb exoskeleton robots.

2. Overview of upper-limb anatomy

This section briefly explains the anatomy of human upper-limb. Fig. 1(a) shows the anatomy of human upper-limb and it consists of shoulder complex, elbow complex, wrist joint and fingers. Shoulder complex shown in Fig. 1(b), consists of three bones: the clavicle, scapula and humerus; and four articulations: the glenohumeral, acromioclavicular, sternoclavicular and scapulothoracic, with the thorax as a stable base [125–128]. The glenohumeral joint is commonly referred to as shoulder joint. Basically, the shoulder complex can be modeled as a ball-and-socket joint. The position of the instantaneous centre of rotation (ICR) of the shoulder joint is dynamic and it changes with the position of the upper-arm. ICR is the point on the plane of motion around which all other points are rotating at a specific instant of time. Main motions of the shoulder complex are shoulder flexion/extension (Fig. 2(a)), shoulder abduction/adduction (Fig. 2(b)), and shoulder internal/external rotation (Fig. 2(c)).

The elbow complex includes (see Fig. 1(b)) the elbow joint and the radioulnar joints [125–127,129]. The elbow complex is a compound joint consisting two joints: the humeroradial between the capitulum and radial head, and the humeroulnar between the trochlea and the trochlear notch of the ulnar. In general, the

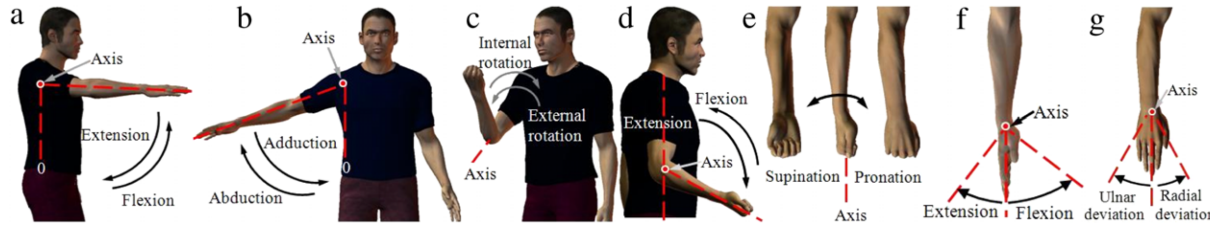

Fig. 2. Upper limb motions. (a) Shoulder flexion/extension. (b) Shoulder abduction/adduction. (c) Shoulder internal/external rotation. (d) Elbow flexion/extension. (e) Forearm supination/pronation. (f) Wrist flexion/extension. (g) Wrist ulnar/radial deviation.

elbow complex allows 2DOF: flexion/extension (Fig. 2(d)) and supination/pronation (Fig. 2(e)).

The wrist joint is shown in Fig. 1(c). The wrist, or carpus, is a deformable anatomic entity that connects the hand to the forearm. It is a collection of eight carpal bones and a surrounding soft tissue structure. The wrist joint possesses 2DOF: flexion/extension (Fig. 2(f)) and radial/ulnar deviation (Fig. 2(g)). Wrist motions are generated around an instantaneous centre. Although it is considered that wrist motions are generated with respect to two axes, certain researchers have identified that the motions are generated with respect to four axes [130]. The wrist flexion axis is different from the extension axis. Similarly, the radial deviation axis and the ulnar deviation axis are also different. Therefore, the wrist is activated through four axes. Although wrist flexion and wrist extension have different axes they are intersected at a point in the capitate. Similarly, radial and ulnar deviation axes are also intersected. When it is considered that flexion and extension share one axis and similarly ulnar and radial deviations share another axis, the slight offset of the rotational axes of the flexion/extension and the radial/ulnar deviation is approximately 5 mm [130–134].

3. Evolution of upper limb exoskeleton robots

This section discusses the evolution of the exoskeleton systems and the key milestones of the historical development. Since the conceptual development in 1883, the upper limb exoskeleton robots underwent a series of sophistications [135] and the key milestones are tabulated as shown in Table 1. The initial concept of the exoskeleton was developed in 18th century by Vangestine [135]. Based on the information available in [135] an exoskeleton robot was first conceptualized as a wearable device that has a capability of providing extra assistance to walk, jump or run for those who are having long term disabilities. This concept became a reality only after 40 years, when the very first exoskeleton robot was designed in 1936 [25]. This exoskeleton robot was attached to a wheelchair and the device was used as a mechanical feeder for serving food. As shown in Fig. 3, a seasaw cradle support was fitted into the arm and the feeder was operated by foot [25]. The wearer was able to feed by herself and the actuation of the elbow flexion/extension was provided through the foot pedal. Motivated by this initial design of "foot operated feeder", several other feeders were developed by Goergia Warm Spring Foundation [136]. Balanced forearm orthosis, bird cage feederseg-ment arm feeder are some of the later developed feeders [136]. C clamp feeder was developed in 1950 and it was fitted onto a table. Later this feeder evolved into a system that can be fitted directly onto the user's body and it was operated using body power.

Within the first generation of exoskeleton research, some studies have focused on developing actively controlled orthoses [137]. In 1960 US Department of Defence initiated the first generation of exoskeleton system that can be used as a suit of body armour [138]. During the same period Cornel Aeronautical Laboratory started developing Man–amplifier systems. The motion intention of the user should be identified to generate the control commands of the power assist robot. Therefore, in 1960, research work began to investigate myoelectrically controlled stimulator to generate motor commands to emulate a paralyzed muscle [139]. As a result, in mid 1960s General Electric Co. (GE) developed the very first physical model of the actuated first generation exoskeleton robot [140]. It was a robotic master slave device and the operator controls the movements of the robot while locating him/herself inside the robot. GE had the intention of using it for many hazardous applications such as bomb disposing, underwater constructions, nuclear power plants and in outer-space [140]. At the beginning of 1980, Rabischong developed a robotic upper limb orthotic device [141]. A breakthrough in the exoskeleton designs came in early 1990s, where Kazerooni et al. developed the second generation of exoskeleton robots with the concept of human robot interaction [28,29]. At the same time Kanagawa Institute of Technology, Japan developed a power assist suit in order to assist human limb motions [142]. During the 1990s, studies were started on developing a Hybrid Assistive Limb (HAL) by Sankai et al. [143]. The advancement of HAL gone through several cycles of developments at different stages and now it is a commercially available assistive suit to be used for daily motions [144]. In the beginning of the 21st century, Rahman et al. developed the very first active orthoses [145]. Following these developments, Nef et al. developed a robotic upper limb assistive system, ARMIN in 2005 and it is available now commercially for the upper limb rehabilitation [30,146]. Wolbrecht et al. proposed a control framework to promote robot assisted neuro-rehabilitation [147]. Rotary series elastic actuators are used for exoskeleton robots in 2009 [148]. A framework is developed by Ugurlu et al. in 2012 for the sensorless torque estimation in exoskeleton robots [149]. A significant advancement is made during this period from the initial conception of mobility assistance to the assistive robots [150,151]. Modern concepts of upper-limb exoskeleton robots will be elaborated more at the latter part of this paper.

Fig. 3. Foot operated feeder [25].

Table 1
Milestones of evolution of upper-limb exoskeleton systems.

Year	Milestone	Era
1883	• Initiation of the concept for exoskeletons – the concept of mobility assistance [135]	Concept Generation
1936	• First body powered mechanical feeder Foot operated feeder – Georgia Warm Spring Foundation – Mainly for polio victims [25]	Mechanical feeders for meal assistance using body power
1950	• C clamp feeder – Georgia Warm Springs Foundation – Fitted to the table [25]	
1953	• First powered feeder fitted directly to the body Corset-based feeder - Georgia Warm Springs Foundation [25]	
1956	• Studies on active controlled orthoses [136]	Initiation of studies on active orthoses
1960	• Developments on first generation of the exoskeletons Suit of armour at US Department of Defense Man – amplifier at Cornel Aeronautical Laboratory [137]	First generation of exoskeletons
1961	• First attempt to use biological signals for controlling Myo-electrically controlled stimulator for paralyzed muscle [138]	
1966	• First powered exoskeleton robot Robotic master – slave configuration-Actuated by hydraulic actuators [26]	
1982	• Robotic upper-limb orthoses [139]	
1990	• Second generation of the exoskeletons Extenders - Human Machine Interface with direct contact forces between wearer and the extender [28], [29] Power assist suit – Japanese Kanagawa Institute of Technology [140]	Second generation of exoskeletons
1998	• Approach to analyze kinematic data collected in the robot-aided neuro rehabilitation procedure [159]	
2000	• First powered orthoses [141]	
2005	• Upper-limb exoskeleton: ARMin -1 (Initial design) [47]	Third generation of exoskeletons with commercialize products
2008	• Lyapunov-based control framework capable of compliantly assisting patients to complete reaching movements [163]	
2009	• Commercially available exoskeleton for rehabilitation ARMinIII – ARMEO Products commercial device [99]	
2009	• Usage of rotary series elastic actuators [142]	
2012	• Sensorless torque estimation and control [143]	
2012	• HAL -5 [144]	

4. Requirements and design difficulties

The design specifications of an upper-limb exoskeleton heavily depend on its application and the applied limb segment. Complex nature of the human upper-limb anatomy makes it difficult to design an exoskeleton robot to assist upper-limb movements.

ICR at elbow and shoulder joints generally change with the joint motion [124]. Furthermore, joint axes misalignments between human and robot can also occur during the motion [152]. This joint misalignment can lead to high interaction forces and torques at the connecting points. It also leads to a high cognitive load as well as a high contact pressure and as a result such misalignments can lead to produce discomfort to the user. Different techniques are used in upper limb exoskeleton robots to minimize effect of joint axes misalignment. In MEDARM, additional joints that allow the exoskeleton to shift its centre of rotation (CR) of shoulder are utilized to overcome the effect of ICR motion [59]. Motion of CR is taken into account in [153] by designing a special linage mechanism for the shoulder joint. A compliant actuation system is used in NEUROExos to avoid joint axes misalignments at the elbow joint [154]. In [155], Jarrasse and Morel formulated hyperstaticity to prevent undesired forces when the robot/user joints are misaligned. Ergin et al., have proposed an exoskeleton robot which can adjust its joint axes to have a perfect match between human joint axes and the device axes [98]. In many cases, complex mechanisms are proposed to overcome the effect of joint axes misalignment in exoskeleton robots and such methods are practically infeasible in portable designs. In [31], a mechanism was designed for the shoulder to cancel out the ill effects caused by the position difference between the CR of the robot shoulder and the human shoulder. However, the robot is incapable of generating motions above the shoulder level. An exoskeleton mechanism for the lateral and frontal abduction of human shoulder has been proposed in [40]. Major consideration of the design was on the location of the CR of the humerus with respect to the scapula in order to move it with the shoulder CR of the human.

Since an upper-limb exoskeleton robot also directly interacts with the human user, safety is imperative. The mechanical singularity of the robot should not occur within the movable regions of the motions or it should be placed at an anthropometrically desirable location. Some designs have the ability to accommodate these singularities [43,47].

A wrist exoskeleton robot should provide the axes offset of wrist flexion/extension axis and wrist radial/ulnar axis. So far several exoskeleton robots have been developed for wrist joint motions [15,39,41–43]. The axis offset of wrist axes have been considered in some of them [15,39]. In majority of designs, the wrist flexion and extension generate through one axis while allowing wrist radial and ulnar deviation to generate through another axis. However, the work in [130] shows that the wrist motions should require four axes rather than two. Therefore, the exoskeleton robot for wrist motions should provide individual axes for wrist flexion, wrist extension, wrist radial deviation and wrist ulnar deviation to generate biomechanically similar wrist motions.

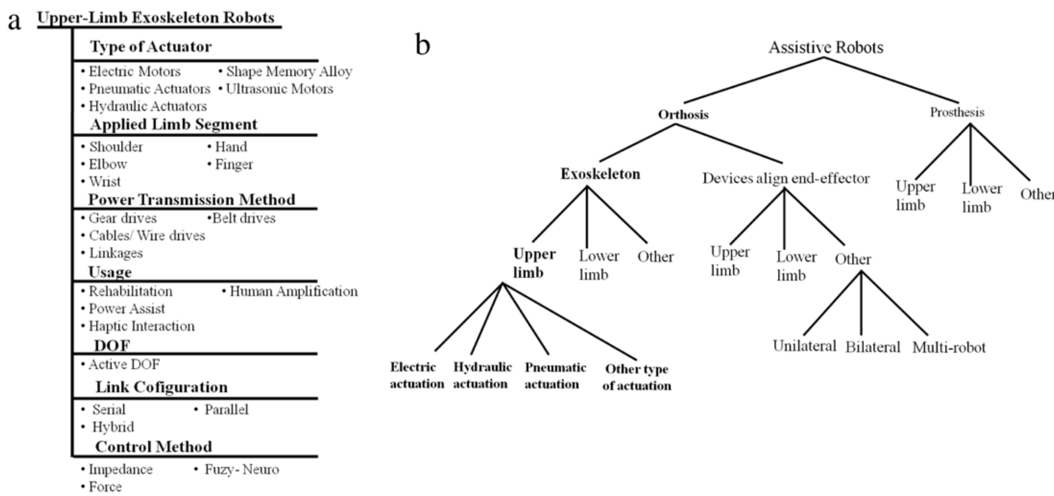

Fig. 4. Classification of exoskeleton robot systems. (a) Methods of classification of upper-limb exoskeleton robots. (b) A classification of upper-limb exoskeleton robots based on the actuators use.

5. Classification of upper-limb exoskeleton robots

Upper-limb exoskeleton robots can be classified in several ways (see Fig. 4(a)) considering characteristics of their mechanical designs and/or software systems (control methods).

(1) **The applied segment**
Under this category, the upper-limb exoskeleton robots can be classified as hand exoskeleton robot, forearm exoskeleton robot, full upper-limb exoskeleton robot or combined segment exoskeleton robot.

(2) **The DOF**
Here, the upper-limb exoskeleton robots can be classified according to the number of active joints or in other words DOF as 1DOF, 2DOF, 3DOF *etc.*

(3) **The method of actuation**
This classification is based on the type of actuators used in the exoskeleton robot such as electric, pneumatic, hydraulic or other types of actuators that include hybrid methods;

(4) **The method of power transmission**
Here the classification is based on the power transmission method such as gear drive, cable drive, linkage mechanism, and other methods; other methods include belt drive, ball screw drive, a combination of two or more methods (hybrid);

(5) **The application domain**
Upper-limb exoskeleton robots can be classified in accordance with the intended application such as rehabilitation robots, assistive robots, human amplifiers, haptic interfaces or other uses;

(6) **The linkage configuration**
Based on the linkage configuration, the upper-limb exoskeleton robots can be classified as serial, parallel or hybrid;

(7) **The control method**
This category classifies the upper-limb exoskeleton robots based on their control methods such as impedance control, force control, fuzzy-neuro control or other control methods.

In this paper, exoskeleton robots are organized according to the actuators used in their hardware systems as (refer Fig. 4(b)):

(a) Type *A*—electric actuation
(b) Type *B*—hydraulic actuation
(c) Type *C*—pneumatic actuation
(d) Type *D*—other types of actuation.

Tables 2–5 respectively show Type *A*, Type *B*, Type *C* and Type *D* exoskeleton robots with a concise comparison. Each table provides a comparison of [56,3,16,5] hardware designs of robotic exoskeleton systems respectively. Type *D* systems include hardware systems which do not have an actuation method or having more than one method to the other three types. In each table the hardware systems are compared and tabulated with respect to their location of application in the body, DOF, type of actuators, power transmission method and application domain of the robot. The country of origin of a hardware system is mentioned in the tables and it is chosen considering the affiliation of the first author of the relevant publication.

6. Review of hardware systems

Upper-limb exoskeleton robots have been used as an assistive device [16,17,19,20,41,156], a rehabilitation device [9,12–14,42,59,60,77,79,80,83,88,91,93–98,100,101,104,106,108,109,112,157] a human amplifier [15,18,44], a haptic interface [23,64,72] and an impairment evaluation device [2,58,76]. Most of the devices use at least a passive DOF to achieve additional workspace so that the user feels more comfortable due to the extra space provided in the design [11,12,72,75–78,84,90,94,96,98,100,102,109]. Majority of upper limb exoskeleton systems use serial link structure. Some robots have adopted combined serial–parallel link configurations [11,20,93,104,157].

Majority of the devices use electric motors for actuation purposes. In some cases pneumatic actuation methods have been used [21,41,42,54,56,61,103,106,108,109]. However, hydraulic actuation methods are rarely used in upper-limb exoskeleton robots. In addition, recently several hardware systems use alternative actuation methods or a combination of the conventional actuation methods.

Among the compared hardware systems in tables (Tables 2–5), more than 72% exoskeleton robots use electric motors as the actuator. About 20% of exoskeleton robots were actuated pneumatically. Hydraulic actuation was utilized by only about 5% of them and about 3% of the hardware systems use alternative or hybrid actuation methods. The usage of actuation methods by the hardware systems is illustrated in Fig. 5.

Table 2
Comparison of Type *A* upper-limb exoskeleton robots.

Country	Reference	Locations of application	Active DOF	Actuator	Power transmission method	Application domain of robot
Japan	Gopura and Kiguchi [15]	Shoulder, elbow and wrist joints and forearm	7	DC servo motors	Cable and gear drives	Power assist
	Kawasaki et al. [9]	Wrist joint, fingers and forearm motion	18	Servo motors	Linkage mechanism and gear drive	Rehabilitation therapy
	Otsuka et al. [16]	Shoulder and elbow	4	DC Motors	Gear, Tendon drive	Meal assistive robot
	Hasegawa et al. [17]	Shoulder, elbow and wrist	4	DC motors	Gear drive	Meal assistive robot
Greece	Papadopoulos and Patsianis [40]	Shoulder joint	2	Servo motors	Geneva mechanism conjunction to a four-bar mechanism	Help people with muscle atrophy and accelerate recovery
Italy	Frisoli et al. [23,72]	Shoulder and elbow joints	4 Passive-1	Frameless DC permanent magnet torque motors	Tendon drive	Haptic interaction in virtual environments
	Johnson et al. [53]	Shoulder and elbow joints, forearm motion	3	Electric motors	Cable drive	Assistive robot and rehabilitation
	Pignoloet al. [73,74]	Shoulder, elbow and forearm	6	DC motors	Gear drive	Virtual exercise, rehabilitation
United States of America (USA)	Rosen et al. [18,44]	Shoulder and elbow joints	2	DC motors	Cable and gear drive	Power assist
	Perry and Rosen [43]	Shoulder, elbow and wrist joints and forearm	7	Brushed motors	Cable drive	Rehabilitation, virtual reality simulation and power assist
	Gupta [10,45]	Elbow and wrist joints and forearm motion	5	Electric motors	Direct drive	Training and rehabilitation in virtual environments
	Martinez et al. [75]	Shoulder, elbow and forearm joints	5 Passive-3	Electric motors Pneumatic muscles	Bowden cables	Increase task performance of daily tasks
	Park et al. [76]	Shoulder, elbow and wrist joints and forearm	7 Passive-2	DC motors	Cable mechanism	Diagnosis &treatment of neurological injury
	Yupeng et al. [77]	Shoulder, elbow, wrist, and hand open close	8 Passive-2	DC motors	Gear drives and linkage	Stroke rehabilitation
	Yupeng et al. [78]	Shoulder, elbow, forearm and wrist	4 Passive-2	DC motors	Gear drives	
	Carignan et al. [57]	Shoulder and elbow joints, forearm motion	5	Brushless DC motors	Slip clutch, gear drives	Rehabilitation and exercise therapy
	Ying et al. [79,80]	Shoulder and elbow	5	DC motors	Cable drive	Neural rehabilitation
	Pehlivan et al. [81]	Forearm and wrist	4 Passive-1	DC motors	Cable drive	Stroke and spinal code injury rehabilitation
	Pehlivan et al. [11]	Wrist	3	DC motors	Cable drive	Stroke and spinal code injury rehabilitation
	Ragonesi et al. [12]	Shoulder and elbow	2 Passive-2	Series elastic actuators	Gear drive	Rehabilitation
	Stienen et al. [2]	Elbow and wrist	4	DC motors	Gear drive	Quantification of Upper Limb Motor Impairments
	Martinez et al. [13]	Wrist	3	DC motors	Gear drive, cable drive	Stroke rehabilitation
	Myomo—mpower 1000 [158]	Elbow	1	DC motors	Gear drive	Stroke rehabilitation
Spain	Ruiz et al. [52,71]	Elbow and wrist joints and forearm motion	3	Continuous current motors	Gear drive	Tremor Assessment and Suppression
	Galiana et al. [14]	Shoulder	1	DC motor	Bowden cables	Post stroke shoulder rehabilitation
Germany	Luis et al. [82]	Elbow	1	DC motors	Gear drive	Support elbow motion
Canada	Ball et al. [58]	Shoulder, elbow and wrist joints	3	Electric motors	Cable drive	Rehabilitation and assessment
	Ball et al. [59,60]	Shoulder, elbow joints	6	Electric motors	Cable drive	Rehabilitation
	Rahman et al. [156]	Shoulder and elbow	2	DC motors	Gear drive	Assist activities of daily living

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Table 2 (*continued*)

Country	Reference	Locations of application	Active DOF	Actuator	Power transmission method	Application domain of robot
China	Chou et al. [64]	Shoulder, elbow and wrist joints and forearm motion	7	Electric motors	Steel wires	Haptic interaction
	Liu et al. [83]	Shoulder, elbow and forearm	10	DC motors	Belt drive	Rehabilitation
	Songet al. [84,85]	Elbow and wrist	3 Passive-4	DC motors	Cable drive	Upper-limb rehabilitation
France	Jarrasseet al. [86,87]	Shoulder, elbow and wrist	7	DC motors	Ball–Screw, cable transmission and belts	upper limb rehabilitation
	Garrec et al. [88]	Shoulder, elbow and wrist	7	DC motors	Ball screw and cable transmission	Rehabilitation
Netherland	Schiele andVisentin [89,90]	Shoulder, elbow, and wrist joints and forearm	8 Passive-6	Motors	Tendons	Force-feedback telemanipulation
Taiwan	Guan et al. [91]	Shoulder and elbow	7	DC motors	Gear drive	Rehabilitation for patients after stroke
Brazil	Andrey et al. [92]	Elbow	1	DC motors	Screw drive	Rehabilitation and motor control assessment
	Nunes et al. [93]	Shoulder and elbow	4	DC motors	Cable drive	Rehabilitation
South Africa	Naidu et al. [19]	Shoulder, elbow, wrist and hand	7	DC motors	Gear drive	Assisting activities of daily living
Korea	Ivanova et al. [20]	Shoulder, elbow and wrist	7	DC motors	Parallel links, gear drives	Assisting activities of daily living
Singapore	Esmaeili et al. [94]	Forearm and wrist	1 Passive-2	DC mootor	Cable drive	Rehabilitation
India	Manna et al. [95]	Shoulder, elbow, forearm an wrist	10	DC motors	Gear drive	Upper limb rehabilitation
Poland	Gmerek [96]	Shoulder and elbow	4	DC motors	Gear drive	Upper limb rehabilitation
Turkey	Ozkul et al. [97]	Shoulder, elbow, forearm and wrist	6	DC motors	Cable drive	Upper-limb rehabilitation
	Ergin et al. [98]	Shoulder and elbow	6 Passive-1	DC motors	Gear drive, belt drive	Upper limb rehabilitation
Switzerland	Nefet al. [30,47–49, 99]	Shoulder and elbow joints	6	DC motors	Cable and gear drives and linkage	Upper-limb rehabilitation
Romania	Alutei et al. [112]	Forearm, index and middle fingers	7	DC motors	Gear drive	Rehabilitation
Sri Lanka	Gunasekara et al. [159]	Elbow, Forearm and wrist	4 Passive-2	DC motors	Gear drives	Power assist

Table 3
Comparison of Type *B* upper-limb exoskeleton robots.

Country	Reference	Locations of application	Active DOF	Actuator	Power transmission method	Application domain of robot
USA	Mistry et al. [50]	Shoulder, elbow and wrist joints and forearm motion	7	Hydraulic actuators	–	Human arm movement study
Italy	Lenzi et al. [100,154]	Elbow joint	1 Passive-4	Hydraulic pistons	Steel wire ropes and Bowden cables	Upper-limb rehabilitation
Germany	Pylatiuk et al. [101]	Elbow joint	1	Hydraulic pistons	–	Upper-limb rehabilitation

Table 4
Comparison of Type *C* upper-limb exoskeleton robots.

	Reference	Locations of application	Active DOF	Actuator	Power transmission method	Application domain of robot
Japan	Sasaki et al. [41]	Wrist joint	1	McKibben type pneumatic muscle	–	Motion assist
	Kobayashi and Hiramatsu [61]	Shoulder, elbow and wrist joints	6	Pneumatic actuators	–	Provide muscular support
	Eiichi et al. [102]	Shoulder and elbow	2 Passive-2	Pneumatic rotary actuators and pneumatic cylinders		Upper limb power augmentation
	Takaiwa et al. [157]	Wrist	3	Pneumatic cylinders	–	Wrist rehabilitation
United Kingdom	Tsagarakis and Caldwell [42]	Shoulder, elbow and wrist and forearm motion	7	Pneumatic muscle actuators	Cable drive	Upper arm rehabilitation
Korea	Lee et al. [103]	Shoulder, elbow and wrist joints, forearm motion and fingers	13	Pneumatic actuators	Linkage mechanism	Teleoperation of robots
USA	Cramer et al. [54]	Hand and wrist joint	3	Pneumatic actuator	–	Hand therapy
	Sugar et al. [56,62]	Shoulder, elbow and wrist joints	4	Pneumatic muscles	Cable drive	Upper extremity repetitive therapy
	Kleinet al. [104,105]	Shoulder, elbow and wrist	6	Pneumatic actuator	–	Neurorehabilitation
	Allington et al. [106]	Forearm, Wrist	2	Pneumatic actuator	–	Rehabilitation after stroke
Spain	Moraleset al. [107,108]	Shoulder and elbow		Pneumatic actuator	–	Rehabilitation
Brazil	Ramos et al. [21]	Shoulder and elbow	6 2 Passive-1	Pneumatic muscle actuators	Pneumatic muscle actuators, cable drive	Complete task of lifting a payload
China	Jiang et al. [109]	Shoulder, elbow and forearm	8 Passive-1	Pneumatic muscle actuator	Cable drive	Upper limb rehabilitation

Table 5
Comparison of Type *D* upper-limb exoskeleton robots.

Country	Reference	Locations of application	Active DOF	Actuator	Power transmission method	Application domain of robot
Korea	Bae et al. [110]	Wrist and index finger	3	Pneumatic cylinder and linear motors	–	Hand rehabilitation
Japan	Ohnishi et al. [111]	Shoulder, elbow, forearm and wrist		Hydraulic bilateral servo actuator	Cable drive	Upper limb power assist
USA	Daniel et al. [12]	Shoulder and elbow	7 2 2-passive	Series elastic actuator	Elastic bands	Upper limb power assist

The power transmission method to be used in the joint/moving link heavily depends on the actuation method. Along with electric motors, the power transmission may include gear drives, cable drives, belt drives or ball screws. In pneumatic drives, pneumatic piston and cylinder or cable drives are used for power transmission. Power transmission methods for hydraulic and hybrid actuators vary according to the application. From the exoskeleton systems covered in this review, usage of cable drives for power transmission is about 26% and the usage of gear drives is about 21%. Usage of other methods is about 25%. Other methods include linkages, ball screw drives or a combination of two or more conventional power transmission methods. Combination of actuation methods and the power transmission methods in exoskeleton systems are illustrated Fig. 6.

The hardware systems of key upper-limb exoskeleton robots are reviewed in the next sub sections under which the classification is presented. Certain exoskeleton systems are selected based on their key technological features in mechanical design.

6.1. Upper-limb exoskeleton robots with electric actuation

Electric motors are the commonly used actuator for the upper-limb exoskeleton robots due to their advantages such as fast operations using high speed motors, precision and higher

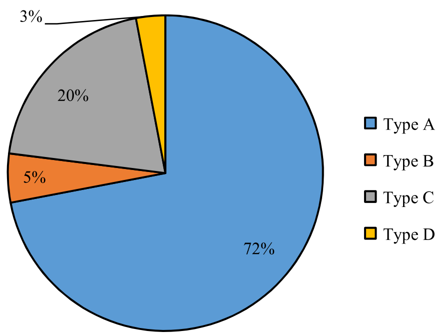

Fig. 5. Usage of actuation method for upper limb exoskeleton systems.

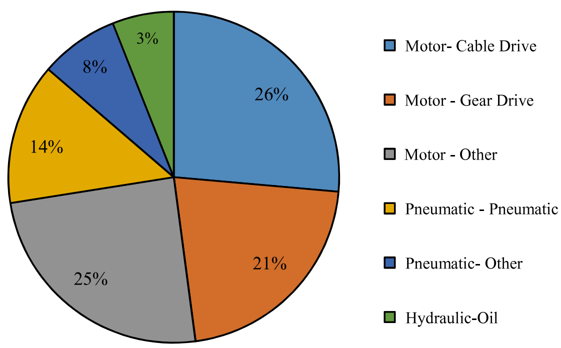

Fig. 6. Usage of power transmission method for upper limb exoskeleton systems.

controllability using advanced motion control. In this sub section, electric motor actuated upper-limb exoskeleton robots are briefly reviewed taking state-of-the-art robots as examples.

6.1.1. CAREX [79,80]

The CAREX is a cable driven 5DOF (see Fig. 7(c)), exoskeleton robot [79,80] developed by Mao and Agrawal for neural rehabilitation. The design of the robot is based on three cuffs, one for shoulder, one to wrap around the upper arm and the other to hold the forearm. The arm motion is controlled by cables attached to the cuffs that are driven by motors mounted outside separately. In CAREX, the design concept is not in line with the traditional definition of the exoskeleton; joints and links have direct correspondence with the human limbs and joints respectively. As the system is designed with no links and joints, alignment of human joint axis of rotation with the robot joint axis is no longer an issue. The cables are routed from proximal segments of the arm to distal segments, rather than having independent sets of cables for different segments. This permits force field control, which has been demonstrated to be successful in gait training of stroke survivors [79]. Unique structure of the CAREX makes the design free of segments and therefore it does not require length adjustments or joint axes alignments. Furthermore, it does not restrict the natural DOF of the human arm and is lighter than conventional exoskeletons. The modular architecture and the cable routed power transmission mechanism make this an important study for the future design concepts.

6.1.2. Upper-limb exoskeleton robotic project of saga university, Japan [15,31,36,153]

The upper-limb exoskeleton robot designed at Saga University has drawn the attention of the researchers due to its unique features that mimic the nature of shoulder and wrist joints of human. Kiguchi et al. have proposed a moving CR mechanism for the shoulder joint [31]. The mechanism moderately adjusts the distance between the upper arm-robot attachment and the CR of the shoulder joint of the robot in accordance with the shoulder motion. Thus this design attempts to cancel out the ill effects caused by the position difference between the CR of the system shoulder and the human shoulder. The shoulder vertical motion is limited to 90° in this design and as a result the shoulder mechanism was not assessed for motions above the shoulder level. In the first design of this project, the moving CR mechanism of shoulder has been installed into a 4DOF upper-limb exoskeleton robot that can assist shoulder vertical and horizontal flexion/extension, elbow flexion/extension, and forearm pronation/supination motions [33]. The final set-up was installed onto a wheel chair as shown in Fig. 7(a). This early system was then developed into a 7 DOF system as shown in Fig. 7(b) and is named as SUEFUL-7 [15]. In addition to the moving CR mechanism of shoulder, a wrist joint mechanism [39] has been included in the SUEFUL-7 to generate biomechanically similar human wrist motions. In order to capture the user intentions of the motions, a myoelectric control method has been implemented to control the robot by taking input signal from user muscle activity [15].

6.1.3. Anthropometric 7DOF exoskeleton robot: EXO-7 [43]

Anthropomorphic design approach is another important discussion among the researchers as exoskeleton robots are worn by human beings. Therefore anthropometric factors such as sizes and weight of limbs should be given proper considerations in the design. Due to this reason Perry and Rosen [43] have designed anthropometric 7DOF active exoskeleton system, known as EXO-7 which is shown in Fig. 7(e). The anthropomorphic nature of the joints combined with negligible backlash in seven force-reflecting articulations is set as the original characteristic of the EXO-7. Prior to the development of EXO-7, the research team developed few prototypes with lesser DOF and the latest prototype, EXO-7 was designed considering human anthropometry. Therefore, the size of the EXO-7 is similar to the 95th percentile human upper-limb. However, the design can be improved by including the axes off set (refer Section 2) in the wrist joint. In EXO-7, shoulder internal/external rotation and forearm supination/pronation generate from an open human–robot attachment rather than that of the other exoskeleton designs [9,10,36,38] that uses attachment which fully encloses the arm. Therefore, the user can easily wear the robot.

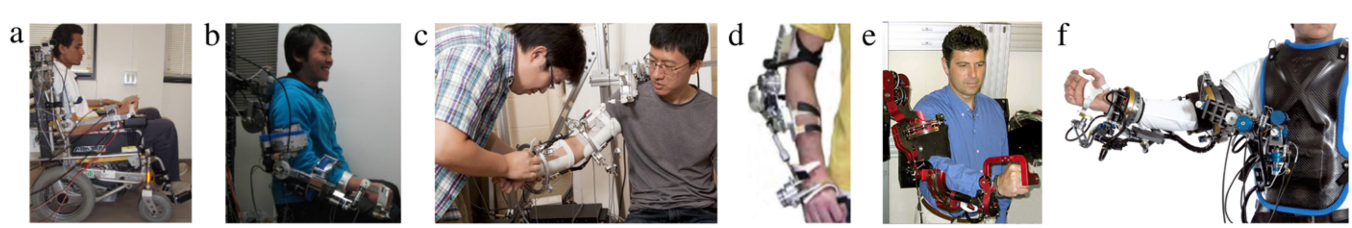

Fig. 7. Electrically actuated hardware systems. (a) 4DOF robot of Saga University, (b) SUEFUL-7 of Saga University, (c) CAREX [160], (d) WOTAS [51], (e) EXO-7 Exoskeleton robot [161], (f) X-Arm-2 [162].

6.1.4. Exoskeleton design for shoulder vertical translation: ARMin III robot [30,47–49,99]

In order to comply with the natural movement, exoskeleton shoulder joint should allow forward and upward translation of the glenohumeral joint in order to accommodate the shoulder flexion/extension and abduction/adduction. As such an exoskeleton robot used in upper-limb rehabilitation must have the ability to adjust its vertical position for different patients. Therefore, the robot should have the adaptability to adjust the link length. ARMin [47,48] is a rehabilitation exoskeleton robot which provides three active DOF for the shoulder and one for the elbow joint. An additional module provides lower arm pronation/supination and wrist flexion/extension. ARMin III [99] is a state-of-the-art exoskeleton robot which has not only the ability to generate the vertical translation from the vertically oriented linear motion module but also the ability to adapt for each patient by adjusting five adjustable segments to fit in the patients having different body sizes. In addition to the vertical translation, ARMin III can generate the motions of shoulder flexion/extension, abduction/adduction, internal/external rotation; elbow flexion/extension, forearm pronation/supination, wrist flexion/extension. As in the EXO-7, in ARMin III, internal/external shoulder rotation is achieved by a special custom-made upper-arm rotary module made out of two half cylinders to easily access the arm of patient. In-cooperated adjustability for different body sizes and the vertical translation mechanism for the shoulder make this robot important to be studied.

6.1.5. Haptic arm exoskeleton design: L-EXOS [23]

In L-EXOS [23], a mechanism was used for the first time allowing the user to insert and remove the arm easily, without a need of inserting the arm through a closed ring structure. L-EXOS is an upper-limb exoskeleton robot for haptic interaction in virtual environment. It is a tendon driven wearable haptic interface with 4DOF. The robot can generate shoulder motions and elbow flexion/extension. The L-EXOS has several unique advantages, since many custom-made components were deployed. The solution of adopting a closed circular bearing has replaced with an open circular component. The interposition of the reduction gear head between the tendon transmissions and the driven joint improved the stiffness of the system.

6.1.6. Wearable orthosis for tremor assessment and suppression (WOTAS) [52,71]

Tremor assessment and suppression is another application of exoskeleton robots [52,71]. A mechanical design for an exoskeleton with tremor assessment and suppression capabilities differs from a conventional exoskeleton system as they do not properly suppress tremor since the orthosis tend to lose alignment with the body instead of suppressing the tremor. The 3DOF upper-limb exoskeleton robot, WOTAS (see Fig. 7(d)) attempted to address the above issue. In the development of WOTAS, specific characteristics for the application of dynamic forces on the arm have been posed. The WOTAS was actuated by electric motors at the wrist and elbow. Its sensory system comprises of kinetic sensors and chip gyroscopes which constantly measure tremor force. It is designed to generate elbow flexion/extension, forearm pronation/supination and wrist flexion/extension.

6.1.7. Portable haptic arm exoskeleton [136]

Portable haptic arm exoskeleton is a 7DOF upper-limb exoskeleton developed under a project for European Space Agency (ESA). The exoskeleton provides shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and wrist ulna/radial deviation. The robot uses DC motors for actuation and capstan type reducers together with gear to transmit power. A capstan reducer is composed of a wheel, wrapped by a cable on the motor shaft and it allows zero-backlash transmission as well as low friction at the expense of a low torque to volume ratio. The exoskeleton served as a prototype of a master device used for teleoperation of future anthropomorphic space robotic arms on the International Space Station (ISS) and is expected to decrease the number of extravehicular activities of the astronauts, even for complex situations. The exoskeleton allows a more intuitive control of anthropomorphic slave arms.

6.1.8. Wrist gimbal [13]

Wrist Gimbal is a 3DOF exoskeleton robot developed for forearm and wrist rehabilitation and it has drawn the attention of the researchers due to its unique wrist design which rectifies the wrist joint axis misalignment between user and the robot. Wrist Gimbal is capable of generating forearm pronation/supination, wrist flexion/extension and wrist ulna/radial deviation. The robot is made out of ABS plus and Aluminum. The exoskeleton robot is capable of allowing accurate joint axes alignment by making use of a handle whose height can be passively adjusted and fixed via a threaded rod and two nuts. Three DC motors were used to actuate the joints and power is transmitted via cables. As a safety precaution, mechanical rubber hard-stops were used for each axis of rotation to prevent movements beyond the design limits.

6.1.9. Exoskeleton robot with parallel link mechanism [45]

Parallel link mechanisms are rarely used in exoskeleton robots. In the literature, only few exoskeletons can be found [10,104] with parallel link mechanisms. Amongst 5DOF haptic arm exoskeleton robot developed in Rice University [10] used electric motors for its actuation and drawn the attention of researchers. In the exoskeleton elbow flexion/extension, forearm pronation/supination, wrist flexion/extension, and radial/ulnar deviation can be generated. A parallel mechanism was used in exoskeleton wrist over a serial mechanism because the compactness of the parallel mechanism and the mechanism allowed a higher torque output, stiffness, and decreased inertia as compared to a similar serial mechanisms [10]. The objective of the project was to provide robot-assisted rehabilitation and training. It used parallel manipulators and 3-RPS [88] platform in the wrist joint. The platform has 3DOF, with actuated prismatic joints. The height of the platform is adjustable to accommodate the forearms of different users.

6.1.10. X-Arm-2 [89,90]

X-Arm-2 was developed by ESA for astronauts and drew the attention of the researchers due to its specific approach to address the joint axis misalignment issue. This exoskeleton robot has been built to allow bilateral control of anthropomorphic space robots with force-feedback. The arm has 8 active DOF and 6 passive DOF. The passive DOF are introduced to alleviate the misalignment of the operator's physiological joints with the robot joints. Furthermore, few actuators were placed remotely in order to optimize the weight of the robot and the power is transmitted via Bowden-cables. X-Arm-2 was attached to the chest, upper arm, forearm and the palm of the operator. The first six joints of the robot interact with the shoulder joint and four of them are actuated. Another three joints make the elbow joints and only two joints are actuated. In order to generate the wrist motion there are five joints out of which only two joints are actuated. Chest-vest and the other larger linkages of X-Arm-2 were made from carbon-fiber composite material.

6.1.11. Exoskeleton for elderly and disabled people [20]

This 7DOF exoskeleton was developed primarily to assist the elderly and disabled people. The exoskeleton was mounted on a wheel chair and the link configuration uses both parallel and serial kinematic structure. Out of the 7DOF, 4 of them were achieved using serial kinematic chain and the remaining 3DOF of the wrist joint were achieved using parallel kinematic structure. In order to control the exoskeleton, admittance controlling was being used. In the design 3 DOF of the shoulder motion are realized using a gimbals type 3DOF mechanism. However, the developers were not yet capable of generating simultaneous motion of the 7DOF since the exoskeleton was not directly attached to the user and only having a single force/torque sensor.

6.1.12. mPower—1000 Arm Brace-Myomo Inc. [158]

mPower 1000 is a commercially available exoskeleton robot, which is designed to fit into a sleeve of the arm with 1 DOF for elbow motion. Even though the main function of the robot is rehabilitation, it can also be worn as an exercising aid to maintain the gains and to assist Activities of Daily Living (ADL). The robotic arm brace is made of a lightweight frame of aerospace metal and includes advanced processing, non-invasive surface sensors for biceps and triceps, and a lightweight battery unit. It employs a proprioceptive biofeedback-based closed loop system to facilitate muscle re-education by both amplifying and rewarding a patient with desired motion in accordance with his or her own muscular activation. The system also includes a suite of software applications and therapy protocols that enable patients to work toward increasing functional activities, measuring progress along the way. In addition, it has on-board controls for easy use and built-in Bluetooth capability for communication with external applications and systems. Design and controlling approach of this system will be important for researchers to take their product to the commercial level.

6.1.13. 6-REXOS: upper limb exoskeleton robot with improved pHRI [159]

The 6-REXOS is a 6DOF upper limb exoskeleton robot which supports elbow flexion-extension, forearm supination-pronation, wrist flexion-extension and wrist ulnar-radial deviation [159]. It has four active rotational DOF and two passive translational DOF, which results in higher DOF than that are available at the human lower arm. Furthermore, two passive DOF are available in the 6-REXOS to allow kinematic redundancy to the exoskeleton robot. Other than redundancy, the 6-REXOS uses several measures to improve the pHRI. Achieving redundancy as well as compliance in the 6-REXOS is a novel design approach. In [159], redundancy in the 6-REXOS is analyzed based on dexterity measures such as manipulability index, minimum singular value, condition number and manipulability ellipsoids. The results show that the kinematic redundancy of the 6-REXOS causes to significantly increase the manipulability index and minimum singular value than that of the existing 4DOF lower arm exoskeleton robots.

6.1.14. Other exoskeleton robots with electric actuation

Ergin et al., [98] proposed an exoskeleton robot for the robot-assisted rehabilitation. The robot allows for movements of the shoulder girdle as well as shoulder rotations. The robot has a novel design to automatically adjust its joint axes in order to have a perfect match between human joint axes and the robot joint axes. In this robot, back-driveable design supports both passive translational movements and independent active control of the center of glenohumeral joint.

The MULOS [53] is an electrically actuated exoskeleton having 3DOF at the shoulder, one at the elbow and one to provide forearm pronation/supination. The shoulder mechanism consists of a serial linkage having an equivalent CR closer to that of the anatomical shoulder. This is a self-contained module in which power transmission is provided by tensioned cables. The elbow and forearm pronation/supination modules are also self-contained. The system provides the advantage of operating three modes of control: as an assistive robot attached directly to the arm to provide controlled movements for people with severe disability, as a continuous passive motion for the therapy of joints after injury and as an exercise device. The joints are actuated by cable drives in such a way as to keep the electric motors closer to the first joint and thus keep required torques to a minimum. An integral slip clutch between the motor and the elbow drive ensures safety in operation.

Although robotic technology shows a significant potential, its effectiveness for upper-limb rehabilitation is still limited due to unavailability of reaching all the necessary movements. A major contributor to this problem is that current robots do not replicate motion of the shoulder girdle despite the fact that the shoulder girdle plays a critical role in stabilizing and orienting the upper limb during activities of daily living. A new adjustable robotic exoskeleton called MEDARM [59] has addressed this issue. It provides independent control of 6DOF of the upper limb. Its joint axes are optimally arranged to mimic the natural upper-limb workspace while avoiding singularity and while maximizing manipulability. The mechanism permits reduction to planar shoulder/elbow motion in any plane by locking all but the last two joints. Electric motors actuate the joint using a combination of cable and belt transmissions designed to maximize the power-to-weight ratio of the robot while maintaining back drivability and minimizing inertia.

A design of a 2DOF exoskeletal mechanism for the lateral and frontal abduction of human upper limb has been proposed in [40]. Major consideration of the design is the location of CR of the humerus with respect to the scapula. The motion of the CR of the shoulder has been obtained using the Geneva mechanism.

In [64], Chou et al. proposed a 7DOF exoskeleton robot in which the motion of each joint is nearly independent and decoupled. This unique design of the device eliminates the problem of singularity. It provides larger work space and larger force feedback than a desktop haptic device.

It is important in an exoskeleton robot to enable the reduction of moving masses and required power to obtain high performance design. The 5DOF exoskeleton robot in [75] has combined electric motors and pneumatic muscle actuators to obtain high performance.

For ergonomics and kinematical compatibility purposes, three passive DOF are implemented to avoid macro misalignments of the shoulder center position and one to avoid micro misalignment of the elbow rotation center with reference to the wrist. Therefore, the robot can increase the comfort and the reduction of interference with other parts of the body.

6.2. Upper-limb exoskeleton robots with pneumatic actuation

Although pneumatic actuators require less maintenance and can be stopped under a load without causing damages, they are less accurate. Therefore, a small number of exoskeleton robots are pneumatically actuated. Two types of pneumatic actuators are used: pneumatic pistons and pneumatic muscles. In this sub section pneumatically actuated upper-limb exoskeleton robots are briefly reviewed by taking available robots as examples.

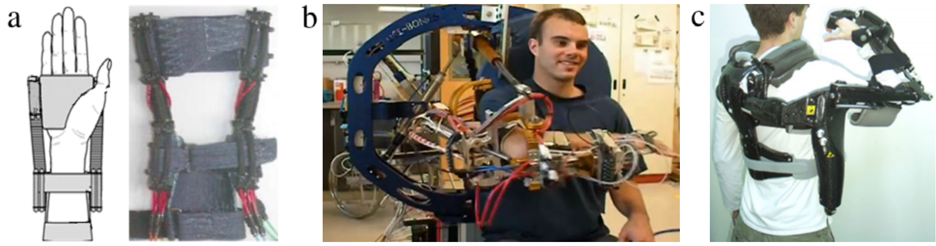

Fig. 8. Pneumatically actuated upper-limb exoskeleton robots. (a) ASSIST [163], (b) BONES [164], (c) RUPERT [165].

6.2.1. *Active support splint (ASSIST) [41]*

Since the exoskeleton robots are wearable devices, they should be of lower weight and the user should not feel the inertia effects that can occur during the operation of the robot. The characteristics of pneumatic muscle has been exploited to design a light weight 1DOF exoskeleton robot named as active support splint (ASSIST) by Sasaki et al. [41]. It has the ability of relieving the restrained feeling when the device is not operated since it consists of McKibben pneumatic muscle and plastic interface. It can be used to assist wrist flexion/extension of elderly or physically weak people. Fig. 8(a) shows the ASSIST. It was designed to have less weight and even lighter than that of a baseball glove. ASSIST is controlled using wearer's EMG signals and signals from a bend sensor. This control strategy has led the user to control the robot with less muscle power. This also results in reducing the user's muscle fatigue.

6.2.2. *7DOF "soft-actuated" exoskeleton design [42]*

By applying a different concept than in ASSIST a 7DOF pneumatically actuated exoskeleton robot has been developed by Tsagarakis and Caldwell [42]. The concept is the application of two pneumatic muscle elements as an antagonistic scheme simulating a biceps–triceps system to provide the bidirectional motion/force. The antagonistic action permits compliance control. Therefore, it has the advantage of safe operations and more human 'soft' interactions that can provide a soft feeling during the manipulation. The other advantages include the low mass and excellent power to weight ratio. The system has the ability to generate motions of shoulder, elbow, forearm, and wrist to rehabilitate the upper-limb. Joint motion on robot has achieved by producing appropriate antagonistic torques through cables and pulleys driven by the pneumatic actuators. Flexible steel cables have been used to couple the muscles and the pulley. The device is expected to use for 3 tasks; as an exercise facility for the joints of the upper limb, as a rehabilitation/power assist orthosis or as a joint power for those with loss/reduced power in the limb and as a motion analysis system.

6.2.3. *Biomimetic orthosis for neurorehabilitation (BONES) [104]*

In exoskeleton designs having shoulder internal/external rotation generally employ a circular bearing element to generate the motion. The 4DOF exoskeleton robot proposed in [104] is unique since it has the ability to generate arm internal/external rotation without using circular bearing elements (Fig. 8(b)). This particular design feature is based on the biomechanics of the human forearm. The device (BONES) is pneumatically actuated and is used for rehabilitation of the upper-limb. It is based on a parallel mechanism that actuates the upper arm by means of two passive, sliding rods pivoting with respect to a fixed structural frame. Four mechanically grounded pneumatic actuators are placed behind the main structural frame to control shoulder motion via the sliding rods, and a fifth cylinder is located on the structure to control elbow flexion/extension.

6.2.4. *Muscle suit: a garment like exoskeleton robot [61,166]*

Kobayashi and Hiramatsu [61,166] have presented a novel concept to the field of exoskeleton robot by developing garment like wearable robot. Although it is referred as an exoskeleton robot it does not have a metal frame. The device provides muscular support for the paralyzed. It uses McKibben actuators driven by pneumatic. The muscle suit is helpful for both muscular and emotional support. The exoskeleton suit has 7DOF, shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and wrist ulna/radial deviation. Contraction and extension of the muscle actuate the joint motion. However, range of motion limitations, slippage and slack of wear, tight fit, difficulty in dressing/undressing and heavy load on joints are the problems that are yet to be resolved. Muscle suit changes the direction of exoskeleton research into a new dimension and possibly future exoskeleton designs will follow this approach making exoskeleton a more user friendly device.

6.2.5. *RUPERT [62]*

RUPERT is developed to provide a low cost, safe and easy-to-use, robotic device to assist the patient and therapist to achieve more systematic therapy at home or in the clinic. It has 4DOF driven by compliant and safe McKibben type pneumatic muscles on the shoulder flexion/extension, elbow flexion/extension, forearm supination/pronation and wrist flexion/extension. The robot provides training of critical reaching and feeding motions for ADL. The lengths of the both upper and lower arm segments can be adjusted to fit a wide range of patient body sizes. RUPERT also bears the ability to measure the wearer's movement and voluntary muscle activity to achieve more systematic therapy. For example, the device can provide real-time, objective assessment of functional improvement.

6.2.6. *Other exoskeleton robots with pneumatic actuation*

The HWARD [54] is a unique desk mounted pneumatically actuated exoskeleton robot. It supports the patient's arm and it is attached to the thumb and fingers. HWARD is a 3DOF device that exercises flexion and extension of the hand and wrist. The aim was to retrain hand grasping and releasing movements using real objects during therapy. This is achieved by providing an unobstructed palm area where various objects can be offered for interaction during exercise. Joint angle sensors in the structure are used to measure the movement of the joints. The hand mentor is the first commercial hand rehabilitation therapy system produced by Columbia Scientific LLC [117,119]. It is a 1DOF exoskeleton device that provides a controlled resistive force to the hand and wrist. The applied force can oppose flexion or assist extension of the hand. It incorporates sensors that monitor the position of wrist and fingers during flexion/extension motions as well as force sensors to measure the force applied on the hand by pneumatic muscles [168].

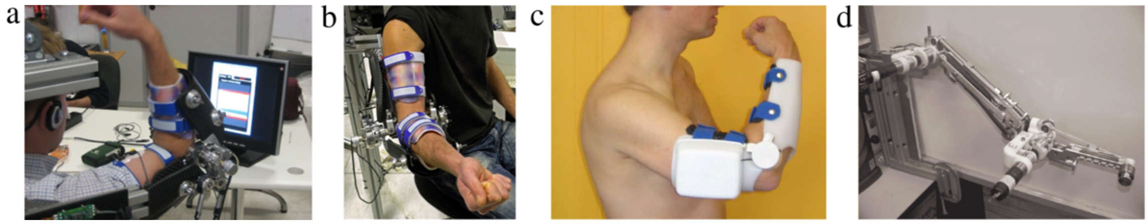

Fig. 9. (a) NEUROExos [167]. (b) HBSS orthosis [111]. (c) SEA powered exoskeleton [12]. (d) Elbow orthosis [101].

6.3. Upper-limb exoskeleton robots with hydraulic actuation

Hydraulic actuators have the ability to generate higher torque as compared to pneumatic or electric systems. The system requires a wider space to accommodate the oil transmitting pipes and conduits. Therefore, hydraulic actuators are very seldom used in upper-limb exoskeleton robots. This sub section briefly reviews the hydraulically actuated upper-limb exoskeleton by taking the available robots as examples.

6.3.1. NEUROexos [100,154]

NEUROexos [154] is a bio inspired, elbow exoskeleton for rehabilitation (see Fig. 9(a)). The design of the robots comprises a double-shell link structure with a wide pHRI area to minimize the pressure on the skin improving the wearability of the robot and the user comfort. Furthermore, NEUROexos comprises of a mechanism for passive self-aligning of the actuated joint axis so as to align with the instantaneous axis of rotation of human joints. The actuation system of the robot is capable of independently regulating the actuated joint position and stiffness. It uses two remote antagonist muscle-like hydraulic pistons as actuators powering the joints by means of steel wire ropes and Bowden cables with an independent joint position and stiffness control. This results in kinematic compatibility between the human and the exoskeleton to ensure a proper torque transmission to the human joint without the risk of overloading the patient's articulations.

6.3.2. Sarcos Master Arm [50]

Sarcos Master Arm [50] is a 7DOF hydraulically actuated exoskeleton robot (Sarcos Master Arm, Sarcos, Inc., Salt Lake City). Its anthropomorphic design mimics a 7DOF of the human upper-limb, such that any joint movement of the user's limb is approximately reflected by a similar joint movement of the exoskeleton. Conversely, torques applied by an exoskeleton joint is reflected to the corresponding joint of the user's limb. The user wields the device by holding on to a handle at the most distal joint and by a strapping of the forearm to the equivalent link of the robot just before the elbow. The shoulder remains unconstrained, but is positioned such that the three shoulder rotation axes of the exoskeleton approximately intersect with the user joint of the shoulder.

6.4. Exoskeleton robots with other types of actuation

Conventional actuators like DC motors, pneumatic actuators and hydraulic actuators have their own merits and demerits. Few robots [110,111] based on hybrid actuator types are available. Fig. 9(b) shows an exoskeleton system with Hydraulic Bilateral Servo System. Additionally, series elastic actuators (SEA) [169] are also employed to develop exoskeleton robots due to their inherent properties like law-pass filer of shock loads, natural torque sensor and possibility of energy storage. Such an exoskeleton robot is described below.

6.5. SEA powered exoskeleton robot [12]

WREX [170] is 4DOF gravity balanced upper-limb exoskeleton robot for children with muscular weakness. 2DOF are powered by series elastic actuator (SEA) to make able the wearer to lift a substantial weight and to raise the arm above the head. The robot is attached to a wheel chair providing assistance to the shoulder and elbow joints. Usage of SEA provides softness to the user and accurate torque control of the robot. To provide better torque control, series elastic element in the actuator acts as a natural, compliant torque sensor. Multiplication of angular displacement and the spring constant measures the torque and it can be used as a feedback. Motion intention of the user to control the robots is provided by the force/torque sensor between the user and robot. The robot is shown in Fig. 9(c).

In addition to the SEA powered exoskeleton robots fludic actuators are also used in some upper-limb exoskeleton robots. Miniaturized flexible fluidic actuators integrated elbow orthosis is proposed in [101]. The robot is shown in Fig. 9(d).

7. Control systems of upper-limb exoskeletons

The controlling requirements and control objectives of an exoskeleton robot differ considerably from the conventional industrial and field robots. This is mainly due to the reason that human operator is not only the commander of the control system but also a component in the control system. The human operator mainly makes the decisions and the exoskeleton implements the tasks. However, feedback information received by the human operator and the exoskeleton robot keeps interchanging between each other. Therefore, intelligence of the exoskeleton system is enhanced while the power of the human operator is also improved. The principle criterion to control the exoskeleton robot, especially power assist exoskeleton robot is to work according to the user motion intention. This becomes much more important for a physically weak person, who is not capable of generating daily motions properly.

An exoskeleton robot consists of two types of controllers: robot controller and human brain. Those controllers are working parallel to each other. The controller of exoskeleton robot especially power assist exoskeleton robot aims at controlling the robot based on the human motion intention most of the time. However, identifying the exact human motion intention is still under at research level [24]. Therefore, understanding and optimizing the best control method is difficult. Control methods of upper-limb exoskeleton robots can be classified in several ways: based on input information to the controller, controller architecture and output of the controller [171]. Based on input information to the controller, the control methods can be categorized as human biological signal based control methods, non-biological signal based control methods and platform independent control methods. The categorization is shown in Fig. 10. We identified that the categorization based on input signals is more important, since the input signals are essential to identify the human motion. EMG signals have successfully employed in some of upper-limb exoskeleton robots [15,100]. In [15] muscle-model oriented EMG based control method is proposed to control 7DOF upper-limb exoskeleton robot. Since the method is adaptable for the user it can be used for most upper-limb disable persons. Most of the EMG

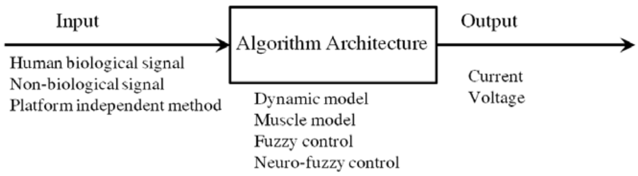

Fig. 10. Categorization of exoskeleton robot control methods.

based control methods used with upper-limb exoskeleton robots are of binary (on–off) nature [100]. Some elderly persons whose motor ability is deteriorated, the environment perception ability may also be deteriorated. In order to cater this problem, the power-assist robot with the perception-assist, which assists not only the user's motion but also the user's interaction with an environment, has been proposed in [172] by Kiguchi et al.

Some exoskeleton robots [172–174] are employed with techniques to extract the human motion intention from non-biological signals to use in their control methods. In these methods human motion intention is identified from other non-invasive sensing instrumentations, such as force/torque sensors or using dynamic model of the human limb. Platform independent control methods operate based on either human biological signal or non-biological signal. Different control strategies are also found in various exoskeleton developments [149,147,159,175] and those are implemented to enhance the features of control system of exoskeleton robot.

In order to force control, force sensors in all the required cases make the system not only expensive but also bulky. Several researchers have attempted to provide a solution to this problem by introducing sensorless force controlling platforms. In 2008, Wolbrecht et al. [147] proposed a control method for assistance as needed to be used for robot-aided movement training following strokes. Three desirable features of the control method are high mechanical compliance, the ability to assist patients in completing desired movements, and the ability to provide only the minimum assistance necessary. The controller uses a standard model-based, adaptive control approach in order to learn the patient's abilities and assist in completing movements while remaining compliant. Assistance-as-needed is achieved by adding a novel force reducing term to the adaptive control law, which decays the force output from the robot when errors in task execution are small. In 2013, Carmichael [176] proposed a novel assistance-as-needed paradigm using models to estimate the assistance needs of the human operator. In this method, an optimization model was developed utilizing the available musculoskeletal models representing the human upper limb to estimate their strength. Ugurlu et al. [149] have proposed method relies on accurately identifying and compensating the joint-level disturbance torques caused by viscous friction, and gravitational loads. The control method comprises of off-the-shelf identification techniques and with introduced additional feed forward torques to compensate the effects of the disturbances at the joint level. Sehoon et al. [175] have introduced a force-sensor-less power-assist control which uses only encoders to obtain the external force information and provides force control performance. Force-sensor-less power-assist control consists of four sections namely, disturbance observer, force observer, model impedance, and feedback controller.

8. Discussion and future directions

Exoskeleton robots are a combination of human intelligence and the machine power. Hence, the power of the human wearer is enhanced by the device. During the past few decades researchers have been constantly working towards the development of higher level intelligence in robots. Their journey is almost succeeded by the recent advancements of technologies in the fields of mechanical engineering, electronic engineering, biomedical engineering and artificial intelligence. Exoskeleton robots are expected to play an important role in the field of rehabilitation, assistive robotics and human power augmentation. So far, several upper-limb exoskeleton robots have been developed for various purposes with their own merits and demerits.

This paper reviewed the major developments in hardware systems in active upper-limb exoskeleton robots to synthesize the pHRI of upper-limb. Since the knowledge on upper limb anatomy is a must towards the development of an effective upper-limb exoskeleton robot, the anatomical features of shoulder complex, elbow complex and wrist joint were explained prior to the discussion on exoskeleton robots. Later, the requirements and design challenges of an upper-limb exoskeleton robot were identified. Although several requirements have already been fulfilled in the existing upper-limb exoskeleton robots, some other requirements are yet to be perfected. Since the human shoulder and the wrist motions are biomechanically intricate, special design efforts have been made when developing exoskeletons for shoulder and wrist. Hardware designs of upper-limb exoskeleton robots can be classified according to the applied segment of the upper-limb, the DOF, method of actuation, power transmission methods, application of the robot and/or the control methods. In this paper, upper-limb exoskeleton robots were classified based on the method of actuation as: electrically actuated, pneumatically actuated, hydraulically actuated and actuated by other means. Key developments of upper-limb exoskeleton robots were compared by indicating their country of origin, references, locations of application, active DOF, actuators, power transmission method and the domain of application.

It is not easy to assist/rehabilitate the human natural upper-limb motion mechanically from the outside of the human body, although many upper-limb robot structures have been proposed. Therefore, the upper-limb robotic structures should further be biomechanically investigated. Due to the physical weakness of the wearer, quality of pHRI is of paramount important to provide comfort and safety in motion assistance. Further investigations are absolutely essential to improve the pHRI.

Furthermore, a mechanism is required to overcome the misalignment between rotational axes of the exoskeleton joint and the axes of user anatomical joints. Especially the shoulder joint mechanism of the upper-limb exoskeleton robot has to be further improved to generate biomechanically similar shoulder motion. Shoulder joint mechanism should allow moving CR and also it should be further refined to overcome the misalignment between rotational axes of the robot joints and the user joints. Even though some of the exoskeleton robots [79,99] were developed to overcome the requirement of the shoulder CR, the proposed methods support only the rehabilitation purpose. Hence, further investigations are imperative to develop the same for the other applications of the exoskeletons, especially for human power assist.

Existing hardware designs of the exoskeleton robots often cause discomfort to the user, and they have not been designed as a permanently wearable devices. Therefore, the ergonomics of the hardware design should be improved to conveniently wear the exoskeleton robots for a longer period of time without any discomfort. The designer should consider not only the outer anatomical features of user but also his physiological demand. Since exoskeleton robots are supposed to be used for daily activities they should be more portable, fashionable, and svelte looking. Existing actuators are often heavy with limited torque and power, often noisy and unnatural in shape which influence negatively for cosmetics of the exoskeleton robots. The actuation technology should be improved to develop miniaturized versions, more durable and high performance actuation for exoskeleton robots. Back-drivability of the transmission is essential in exoskeleton robots to eliminate possible uncomfortability to the user. Although some designs [23,43] have been applied customized back-drivable transmission; more efficient back-drivable systems are essential for the upper-limb exoskeleton robots in the future.

At present mechanical stoppers are introduced together with an emergency stop to upper-limb exoskeleton robots in case of a system failure. In addition, the motion ranges are defined in the control program itself, so that the software based safety control mechanism is also made available. Since human user has worn the exoskeleton robots, the safety aspects should be considered very carefully and needs further sophistications. More efforts should be taken into develop a zero hazard exoskeleton robot system. Thus the users' protection should be ensured in the exoskeleton system itself.

EMG signals are also used as input signal to the controller of power-assist exoskeleton robots [15,100]. Since the brain–machine interface technology is developed to certain extent, in the future the exoskeleton robot will be controlled based on the brain signals so that the user motion intention can be directly reflected than from EMG signals. Electroencephalography (EEG) and electrooculography (EOG) can also be used as biological signals to control the exoskeletons. Most aged people have tremor in their limbs. Although the present exoskeleton controllers are developed to a higher level, the tremor cancellation controlling techniques have not been developed properly. Future exoskeleton controllers should possess more efficient methods to suppress the tremor of limbs. In addition, Micro-Electro-Mechanical System (MEMS) inertial sensors would be a much suitable selection to detect the changes in velocity, orientation and location in exoskeleton robots. This technology empowered to use miniaturized sensors which have low power consumption, low cost, less size and low weight enabling to enhance the function of control methods of exoskeleton robots. In addition, Inertial Measurement Unit (IMU) sensors and Global Positioning System (GPS) can also be introduced into the power assist exoskeleton robots to improve the safety of the wearer and the awareness of the care taker about the wearer. Researchers expect that the future exoskeleton robots would be designed as a 'second skin' [177]. Going beyond that authors envisage that the exoskeleton robot in next decade will also act as communication and entertainment media of the wearer by powering itself using bio-mechanical energy harvesting techniques.

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