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Mechanical Designs of Active Upper-Limb Exoskeleton Robots

State-of-the-Art and Design Difficulties

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Abstract—**Active upper-limb exoskeleton robots have been developing from 1960s. In recent years, the mechanical designs and control algorithms of active upper-limb exoskeleton robots were developed significantly. This paper reviews the state-of-the-art of active upper-limb exoskeleton robots that are applied in the areas of rehabilitation and assistive robotics. In addition, the main requirements of the active upper-limb exoskeleton robot are identified and the mechanical designs of existing active upper-limb exoskeleton robot are classified. The design difficulties of an active upper-limb exoskeleton robot are discussed.**

I. Introduction

THE exoskeleton robots have been considered in the industry, military and medical applications. In recent years, they have been applied in the areas of rehabilitation and power assist for daily activities. The use of exoskeleton robots is increasing in the areas of rehabilitation and power assist in the society in which the number of physically weak (aged, injured and/or handicapped) individuals are increasing.

Active exoskeleton robots were studied for the purposes of industry or medical applications in the 1960s and 1970s [1]-[5]. In addition, some exoskeleton robots were proposed to extend the strength of the human force [6], [7] in early 1990s. In recent years, many active upper-limb exoskeleton robot systems [13]-[58] have been proposed for rehabilitation and power assist. The identification and clarification of the requirements, design challenges and the state-of the-art of an active upper-limb exoskeleton robot is very important to provide solutions for the design difficulties. Therefore, this paper reviews literatures of active upper-limb exoskeleton robots to identify and clarify the requirements, design difficulties and the state-of the-art of active upper-limb exoskeleton robots that are applied in the areas of rehabilitation and assistive robotics. Several researchers [59]-[61] have carried out reviews of exoskeleton robots. However, almost all of their reviews are general review of all types of exoskeleton robots and they have not specially concentrated on the mechanical designs of active upper-limb exoskeleton robot. They rarely reviewed about the mechanical designs of active upper-limb exoskeleton robots. Therefore, the state-of-the-art, requirements and design difficulties specific to the active upper-limb exoskeleton robots are addressed in this review.

In this paper, the upper-limb anatomy toward the development of a proper active upper-limb exoskeleton robot is explained in Section II. The requirements of an active upper-limb exoskeleton robot are discussed in Section III. In Section IV, the design difficulties of developing a proper upper-limb exoskeleton robot are briefly discussed. The performance evaluation methods of mechanical designs of active upper-limb exoskeleton robots are highlighted in Section V. Recently developed important mechanical designs of active upper-limb exoskeleton robots are evaluated after classifying them in Section VI. Final section presents conclusion and areas that should be addressed for future research in the mechanical designs of active upper-limb exoskeleton robots.

II. Upper-Limb Anatomy Towards Development of an Upper-Limb Exoskeleton Robot

As shown in Fig. 1(a), the human upper-limb mainly consists of shoulder complex, elbow complex and wrist joint. In addition, fingers have several joints. 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 [8], [9]. The glenohumeral joint is commonly referred as shoulder joint. The sternoclavicular joint is the only joint that connects the shoulder complex to the axial skeleton. The acromioclavicular joint is formed by the lateral end of the clavicle and the acromion of the scapula. The sternoclavicular joint is a compound joint which has two compartments separated by articular disks. It is formed by the parts of clavicle, sternum, and cartilage of the first rib. In true sense, the scapulothoracic joint can not be considered as a joint as it is a bone-muscle-bone articulation which is not synovial. It is formed by the female surface of the scapula and the male surface of the thorax. However, it is considered as a joint when describing motion of the scapular over the thorax [8]. Basically, shoulder complex can be modeled as a ball-and-socket joint. It is formed by the proximal part of the humerus (humeral head) and the female part of the scapula (glenoid cavity). However, position of the center of rotation of shoulder joint is changing with the upper-arm motions. The main motions of the shoulder complex which are provided by the glenohumeral joint of shoulder complex are shoulder

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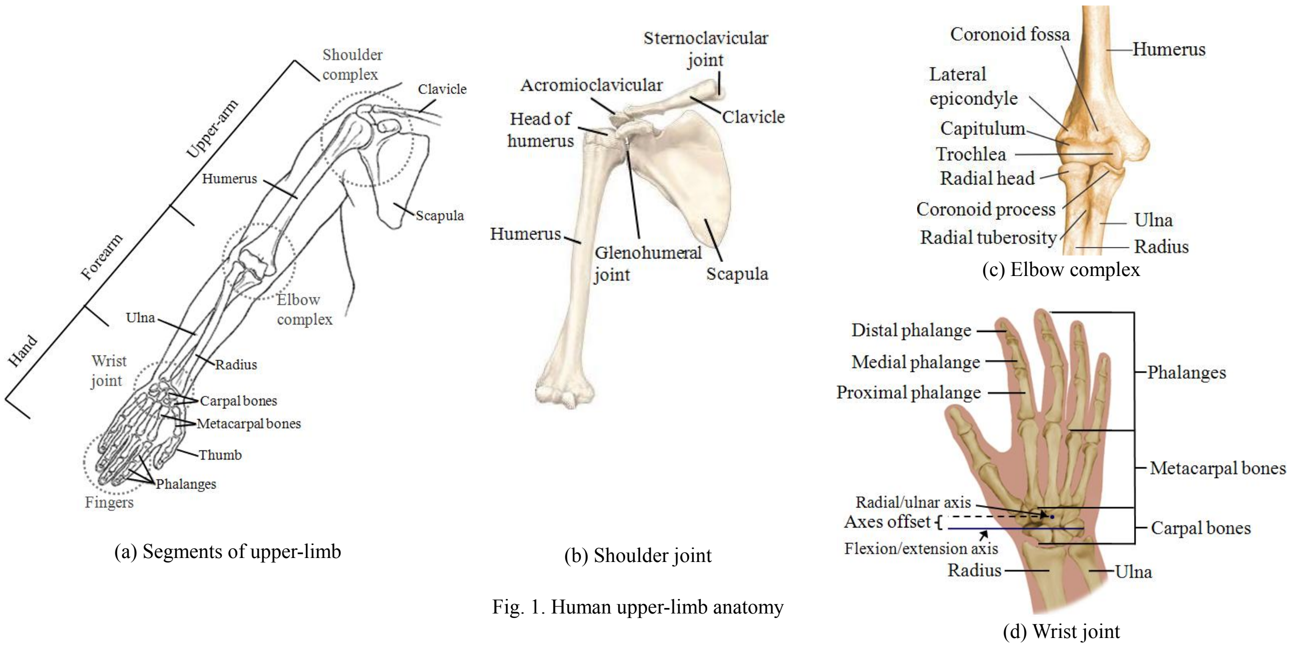


Fig. 1. Human upper-limb anatomy

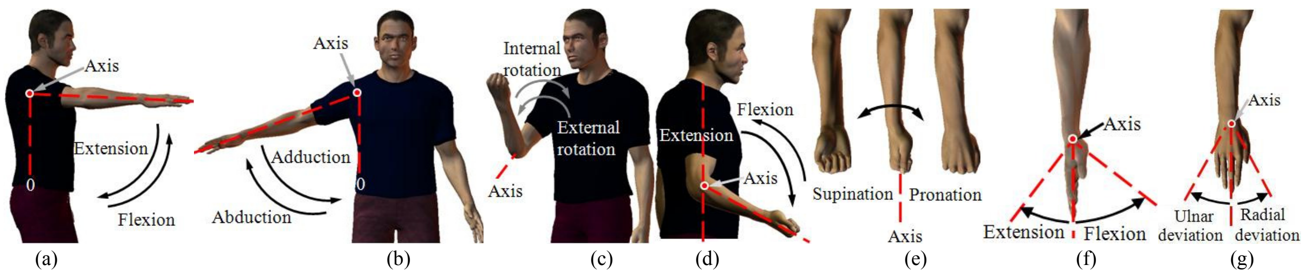


Fig. 2. Human upper limb motions

flexion/extension [Fig. 2(a)], shoulder abduction/adduction [Fig. 2(b)] and internal/external rotation [Fig. 2(c)].

The elbow complex is shown in Fig. 1(c). It includes the elbow joint and the radioulnar joints [8], [10]. The elbow complex is a compound joint consisting of two joints: the humeroradial between the capitulum and radial head, and the humeroulnar between the trochlea and the trochlear notch of the ulnar. The humeroradial joint is a ball-and-socket joint. However, its close association with the humeroulnar and superior radiaulnar joint restricts the joint motion from three to 2DOF. As a whole, the elbow joint complex allows 2DOF, flexion/extension [Fig. 2(d)] and supination/pronation [Fig. 2(e)].

The wrist joint is shown in Fig. 1(d). The wrist, or carpus, is a deformable anatomic entity that connects the hand to the forearm. This is a collection of eight carpal bones and the surrounding soft tissue structure. The wrist contains several joints includes the radiocarpal joint, several intercarpal joints and five carpometacarpal joints. The radiocarpal joint is a condyloid joint formed by the end of the radius and the three carpal bones: the scaphoid, the lunate, and the triquetrum. The wrist joint possesses 2DOF: flexion/extension [Fig. 2(f)] and radial/ulnar deviation [Fig. 2(g)]. Wrist motions are generated around an instantaneous center. The path of the centrode is small, however, customarily, the displacement of the instantaneous center of rotation is ignored and the rotation axes for the flexion/extension and ulna/radial deviation are considered to be fixed. The axes pass through the capitate, a carpal bone articulating with the third metacarpal. Although it is considered that wrist joint motions are generated with respect to the two axes, some research [11] has proved that the motions are generated with respect to four axes. The wrist flexion axis and the extension axis are different. Similarly the radial deviation axis and the ulnar deviation axis are also different. Therefore, the 2DOF of the wrist are activated through four axes. Although flexion and extension motions have different axes they are intersected in a point in capitates. Similarly, radial and ulnar deviations axes are also intersected. When we consider that flexion and extension motions have one axis and similarly ulnar and radial deviations have one axis, the slight offset of the rotational axes of the flexion/extension and the radial/ulnar deviation is approximately 5 mm [8], [12].

III. Requirements of an Upper-Limb Exoskeleton Robot

The requirements of an active upper-limb exoskeleton robot are different in accordance with the purpose of the robot such as rehabilitation, motion assist, human power amplifier and haptic interaction. The important requirements of an active upper-limb exoskeleton robot are briefly discussed in this section.

One of the very important requirement of any system interact with the human is the safety. As the upper-limb exoskeleton robots also directly interact with the human user, safety becomes an important requirement. In addition, several another important requirements have been fulfilled in some existing upper-limb exoskeleton robots. The exoskeleton robot for wrist motion assist has provided the axes deviation of wrist flexion/extension axis and wrist radial/ulnar axis [18]. Movement of the center of rotation of shoulder joint according to the upper-arm motions must be considered to cancel out the ill effect caused by that in design. If upper-arm motions also have to be assisted by the robot as well as forearm motion (i.e., if the exoskeleton have to be attached to both forearm and upper-arm of the user), a mechanism that allows moving of the center of rotation of the shoulder joint must be considered in the upper-limb exoskeleton robot. This mechanism is considered in [13] to cancel out the ill effects caused by the position difference between the center of rotation of the robot shoulder and that of the human shoulder. The mechanical singularity should not be occurred within the workspace of the robot. Some designs have specially considered this in their designs [23], [28].

Although above explained important requirements have been fulfilled, researchers should consider following aspects. The exoskeleton robot for wrist motion assist should have individual axis for wrist flexion, wrist extension, wrist radial deviation and wrist ulnar deviation motions. Mechanical designs of upper-limb exoskeletons can be further improved to reduce their inertia. The weight of the upper-limb robotic system also affect for the portability of the robot also. Therefore, some designs have developed to combine with the wheel chair of the user [17]. However, the upper-limb systems have to be improved to have higher portability.

IV. Design Difficulties

There are many design difficulties for developing a proper mechanical design of an upper-limb exoskeleton robot. Most of them are imposed by the anatomy of the upper-limb. The shoulder complex is one of the anatomically complex areas in the human body. Its center of rotation is changing with its motions. If the robot generates the shoulder motion and is directly attached to the upper-arm of the user, the shoulder mechanism is very important. Design of a proper shoulder mechanism for an upper-limb exoskeleton robot to change its center of rotation with its motions has become one of the difficulties to be accomplished. Some designs [13], [20] have been proposed as partial solution strategy for the shoulder complex.

In the case of the elbow joint, the joint is modeled as a uniaxial hinge joint [10], although it consists of three bones (humerus, ulna, and radius). Therefore, it is not difficult to locate the axis of the rotational center of the exoskeleton robot's elbow joint to be the same as that of the user's elbow joint. In the case of the shoulder joint of the upper-limb exoskeleton robot, however, it is not easy to locate the position of the rotational center of the exoskeleton robot's shoulder joint to be the same as that of the user's shoulder joint since the joint is modeled as a spherical joint and located inside of the user's body.

So far several exoskeleton robots [18], [23], [53], [55] have been developed for wrist joint motions. All of the designs have considered that wrist flexion and extension motions are generated through one axis and wrist radial and ulnar deviation are generated through one axis. Some of the designs of wrist joint have considered about the axis offset of wrist axes [18], [19].

V. Performance Evaluation Methods

Most of the mechanical designs of the upper-limb exoskeleton robots have been evaluated by evaluating the functions of the robot [13]-[17], [53]-[55]. For example, Kiguchi *et al.* [13]-[17] have evaluated mechanical design of upper-limb exoskeleton robot by evaluating the power assist function of the robot.

A widely used quantitative measure to evaluate system performance is bandwidth. Perry and Rosen [23] have used system bandwidth to evaluate performance of their mechanical design of the upper-limb exoskeleton robot. Systems having a higher bandwidth are controllable under higher frequency command signals. The bandwidth is a measure of how successfully tradeoffs are made between weight and stiffness. To maintain performance, the lowest natural frequency of the exoskeleton robot should be above the highest frequency command signal generated by the human. In [23], an oscillating input with increasing frequency was given as a command to the system, to measure resonant frequencies of the exoskeleton robot structure. The magnitude of the input was held to be constant, and the frequency to be increased. In addition, mechanical input-output relationship of the exoskeleton robot has been studied in input and output ends of the transmission [23].

Some exoskeleton robots [18], [24] applied proportional derivate (PD) control method to evaluate the mechanical design of the exoskeleton robot. Kawasaki *et al.* [24] measured the frequency characteristics by the PD control to evaluate the responsibility of the robot. In addition, the joint angle responses have measured to examine the tracking property. To measure frequency characteristics as a linear system, they applied the sinus signal with amplitude of 1 degree. In order to dissipate the effect of gravity, each joint axis of robot was set in the gravity direction. Moreover, a dummy hand having flexible finger joints was attached to the robot to maintain a closed loop and avoid free motion by a passive joint.

Wege and Hommel implemented and evaluated a PID controller for the position control of a hand exoskeleton [33]. The resulting control system allows following of recorded trajectories with sufficient accuracy.

VI. Review of Mechanical Designs of Active Upper-Limb Exoskeleton Robots

Several upper-limb exoskeleton robots have been proposed in recent years [13]-[58]. The recent upper-limb exoskeleton robots have been used for different purposes such as an assistive device, a rehabilitation device, a human amplifier or a haptic interface. Most of them have less than seven DOF (except [23], [24], [44], [45], [47], [54], [55]). The main specialty of the recent mechanical designs of the upper-limb exoskeleton robots is that almost all of the designs have used serial manipulators (Gupta *et al.* have proposed exoskeleton robot with parallel manipulators [26]). Also almost all of the exoskeleton robots have used electric motors or pneumatic muscles as the actuators (except Sarcos Master Arm [47], which is hydraulically actuated).

The active upper-limb exoskeleton robots can be classified according to:

1) the applied segment of the upper-limb (hand exoskeleton robot, forearm exoskeleton robot, upper-arm exoskeleton robot or combined segments exoskeleton robot);
2) the numbers of DOF;
3) the type of the applied actuators (electric motors, pneumatic muscles, hydraulic actuators or other types);
4) the power transmission methods (gear drive, cable drive, linkage mechanism or other);
5) the application of the robot (rehabilitation robots, assistive robots, human amplifier, combined use).

The ways of classification of active upper-limb exoskeleton robots are shown in Fig. 3(a). Since this paper is focused on mechanical designs of the active upper-limb exoskeleton robots, the classification is carried out based on the actuators used in mechanical designs. The classification is shown in Fig. 2(b). The upper-limb exoskeleton robot is classified as:

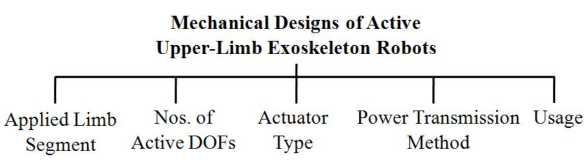
a) Type *A*- actuated by electric motors;
b) Type *B*- actuated by pneumatic muscles;
c) Type *C*- actuated by hydraulic power.

TABLE I, TABLE II and TABLE III show the list of Type *A,* Type *B* and Type *C* exoskeleton robots, respectively.

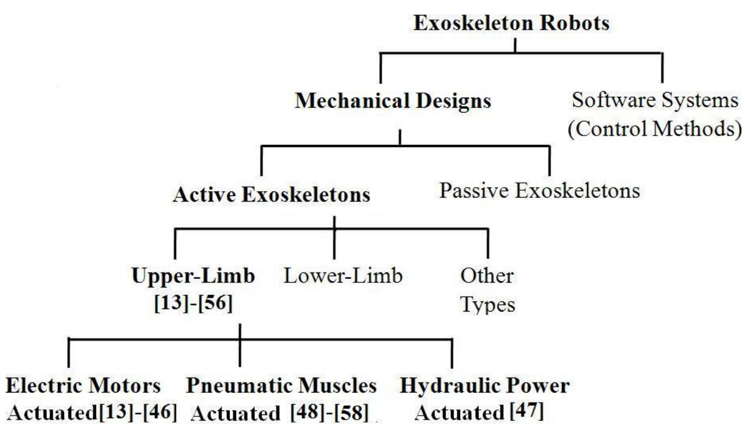
Some of the recently proposed mechanical designs of the active upper-limb exoskeleton robots are reviewed in next sub sections. The logic for selecting particular designs is their novelty of the mechanical design. Other mechanical designs are briefly presented in the latter sub section.

A. Mechanical Design of Shoulder Moving Center of Rotation (CR) Mechanism [17]

A 4DOF active exoskeleton robot [17] with moving CR mechanism [13] of shoulder joint have been proposed in Saga University to assist shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexion/extension, and forearm supination/pronation motions. The exoskeleton robot is installed on a mobile wheel chair since many physically weak persons use it [see Fig. 4(a)]. Therefore, the user does not feel the weight of the exoskeleton robot at all. As a fully attached exoskeleton robot, a unique moving CR mechanism was proposed for the shoulder joint of the exoskeleton robot. The link work mechanism was applied to realize the mechanism. The mechanism cancels out the ill effects caused by the position difference between the CR of the robot shoulder and the human shoulder. Mechanical stoppers have been attached for each individual motion to prevent exceeding of movable range for safety. Also movable ranges of each motion were sometimes set to be narrower than that of average human movable range.



(b) Ways of classification of active upper-limb exoskeleton robots



(a) Classification of active upper-limb exoskeleton robots based on actuators used

Fig. 3. Classification of exoskeleton robots

TABLE I
TYPE *A* UPPER-LIMB EXOSKELETON ROBOTS

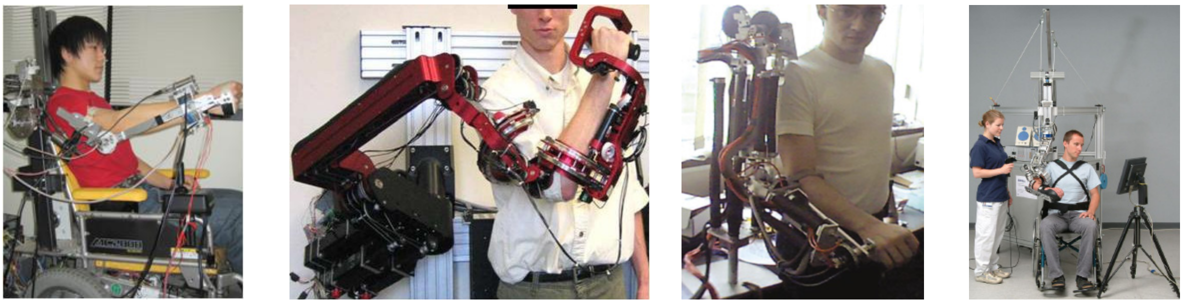
Reference	Locations of application	Active DOF	Actuators	Power Transmission Method	Purpose of the Robot
Gopura and Kiguchi [19]	Shoulder, elbow and wrist joints and forearm motion	06	DC servo motors	Cable and gear drives	Power assist
Papadopoulos and Patsianis [20]	Shoulder joint	02	Servo motors	Geneva mechanism conjunction to a four-bar mechanism	Help people with muscle atrophy and accelerate recovery
Mulas *et al.* [21]	Hand	02	Servo motors	Wire	Hand rehabilitation
Rosen *et al.* [22], [25]	Shoulder and elbow joints	02	DC motors	Cable and gear drive	Power assist
Perry and Rosen [23]	Shoulder, elbow and wrist joints and forearm motion	07	Brushed motors	Cable drive	Rehabilitation, virtual reality simulation and power assist
Kawasaki *et al.* [24]	Wrist joint, fingers and forearm motion	18	Servo motors	Linkage mechanism and gear drive	Rehabilitation therapy
Gupta [26]	Elbow and wrist joints and forearm motion	05	Electric motors	Direct drive	Training and rehabilitation in virtual environments
Nef *et al.* [28], [29], [41]	Shoulder and elbow joints	04 Passive-02	DC motors	Cable and gear drives and linkage	Upper-limb rehabilitation
Mihelj *et al.* [30]	Shoulder, elbow and wrist joints and forearm motion	04 Passive-03	DC motors	Cable and gear drives and linkage	Upper-limb rehabilitation
Johnson *et al.* [31]	Shoulder and elbow joints, forearm motion	03	Electric motors	Cable drive	Assistive robot and rehabilitation
Sarakoglou *et al.* [32]	Fingers	07	DC motors	Tendon drive	Hand exercise
Wege and Hommel [33]	Finger	04	DC motors	Cable & gear drives	Finger rehabilitation
Carignan *et al.* [36]	Shoulder and elbow joints, forearm motion	05	Brushless DC motors	Slip clutch, gear drives	Rehabilitation and exercise therapy
Ball *et al.* [37]	Shoulder, elbow and wrist joints	03	Electric motors	Cable drive	Rehabilitation and assessment
Ball *et al.* [38]	Shoulder, elbow joints	06	Electric motors	Cable drive	Rehabilitation
Rocon *et al.* [46]	Elbow and wrist joints and forearm motion	03	Continuous current motors	Gear drive	Tremor Assessment and Suppression
Frisoli *et al.* [57]	Shoulder and elbow joints	04 Passive-01	Frameless DC permanent magnet torque motors	Tendon drive	Rehabilitation

TABLE II
TYPE *B* UPPER-LIMB EXOSKELETON ROBOTS

Reference	Locations of application	Active DOF	Actuators	Power Transmission Method	Purpose of the Robot
Lucas *et al.* [49]	Index finger	03 Passive-01	Pneumatic cylinder and actuators	Cable drive and linkage mechanism	Pinching assist
Kobayashi and Hiramatsu [50]	Shoulder, elbow and wrist joints	06	Pneumatic actuators	Pneumatics	Provide muscular support
Cramer *et al.* [51]	Hand and wrist joint	03	Pneumatic actuator	Pneumatics	Hand therapy
Sugar *et al.* [52]	Shoulder, elbow and wrist joints	04	Pneumatic muscles	Pneumatics	Upper extremity repetitive therapy
Sasaki *et al.* [53]	Wrist joint	01	McKibben type pneumatic muscle	pneumatics	Motion assist
Noritsugu *et al.* [54]	Fingers	15	Curved and linear type rubber muscles expiration switch	Pneumatics expiration switch	Power assist for hand grasping
Tsagarakis and Caldwell [55]	Shoulder, elbow and wrist joints and forearm motion	07	Pneumatic muscle actuators	Pneumatics	Upper arm rehabilitation
Columbia Scientific LLC [56]	Hand and wrist	01	Compliant air muscles	Pneumatics	Therapy

TABLE III
TYPE *C* UPPER-LIMB EXOSKELETON ROBOTS

Reference	Locations of application	Active DOF	Actuators	Power Transmission Method	Purpose of the Robot
Mistry *et al.* [47]	Shoulder, elbow and wrist joints and forearm motion	07	Hydraulic actuators	Hydraulic oil	Human arm movement study



(a) (b) (c) (d)

Fig. 4. Recent active upper-limb exoskeleton robots. (a) 4DOF Saga University Exoskeleton robot [17]. (b) CADEN-7 [23]. (c) 7DOF Salford University "Soft Actuated" Exoskeleton robot [55]. (d) ARMin robot [28].

B. 7DOF Exoskeleton Robot Design: CADEN-7 [23]

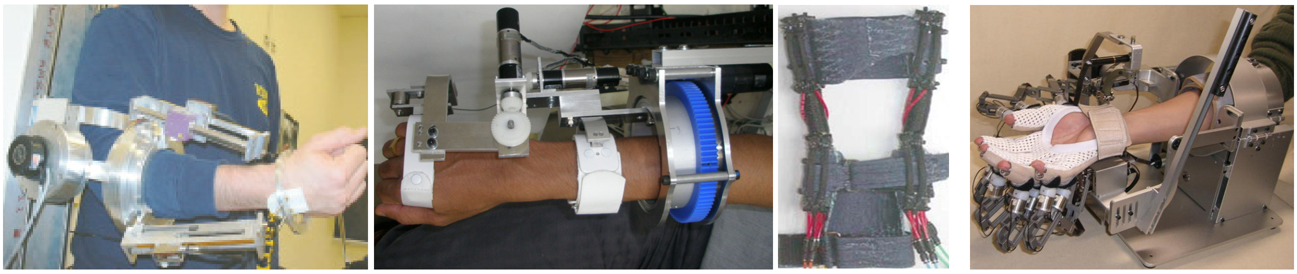
Perry and Rosen [23] have designed anthropometric 7DOF active exoskeleton system shown in Fig. 4(b). The anthropomorphic nature of the joints combined with negligible backlash in seven force-reflecting articulations is set as the original characteristic of the CADEN-7. The other exoskeleton designs [19], [24], [26] have primarily utilized internal/external rotation joints and supination/pronation joints that fully enclose the arm. Therefore, those exoskeleton robots users are required to put their arm from the device shoulder of the exoskeletons, and slide the arm axially down the length of the device through the closed circular bearings. This difficulty is eliminated by the CADEN-7 by using the open human-robot attachment for both upper and lower arm segments. In the cable-driven devices, achieving mechanical joint range of motions to match those of the human arm is a challenging task. The robot generates the motions of shoulder flexion/extension, abduction/adduction, internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and radial/ulnar deviation. Safety precautions have been implemented on three levels, built into the mechanical, electrical, and software designs. In the mechanical design, physical stops prevent segments from excessive excursions. Also, pulleys in some joints are driven purely by friction. This allows the transmission to slip if the force between user and device ever exceeds a set limit. The electrical system is equipped with three emergency shutoff switches: an enable button that terminates the motor command signal upon release, a large emergency stop button and a foot switch.

C. 7DOF "Soft-Actuated" Exoskeleton Design [55]

Some exoskeleton robots have been designed using pneumatic actuators to obtain excellent power/weight ratio and lightness. Tsagarakis and Caldwell [55] have designed a 7DOF prototype upper arm training/rehabilitation exoskeleton robot. The system [see Fig. 4(c)] is able to generate motions of shoulder flexion/extension, abduction/adduction, internal/external rotation, elbow flexion/extension, forearm supinaion/pronation, wrist flexion/extension and radial/ulnar deviation. The original characteristics of the design are use of pneumatic muscle actuators especially as an antagonistic pair. Therefore, the robot provides the antagonistic action which is permitted for the compliance control. It has advantages in terms of safety and human 'soft' interaction which provides a soft feeling in human manipulation. The other advantages of the system are the low mass and excellent power/weight ratio. The system uses braided pneumatic Muscle Actuators (pMA) to have a high power/weight ratio and safety due to the inherent compliance. These pneumatic Muscle Actuators (pMA) have been constructed as a 2 layered cylinder. The structure of the muscles gives the actuator a number of desirable characteristics [55]. Joint motion/torque on the rehabilitation/training arm is achieved by producing appropriate antagonistic torques through cables and pulleys driven by the pneumatic actuators. Since the pneumatic Muscle Actuator is a single direction-acting element (contraction only), two opposed elements are needed for bidirectional motion/force. These two acting elements work together in an antagonistic scheme simulating a biceps-triceps system to provide the bidirectional motion/force.

D. Mechanical Design of Exoskeleton for Shoulder Vertical Height Adjustment: ARMin Robot [28], [29]

ARMin is a four active DOF exoskeleton robot for arm therapy applicable to the training of activities of daily living in clinics [28], [29]. The robot [see Fig. 4(d)] can generate the motions of vertical shoulder rotation, shoulder horizontal



(a) (b) (c) (d)

Fig. 5. Recent active upper-limb exoskeleton robots. (a) 5DOF Exoskeleton robot of Rice University [26]. (b) W-EXOS [18]. (c) ASSIST [53]. (d) 18DOF hand motion assist robot [24].

flexion/extension, internal/external rotation and elbow flexion/extension. Main original feature of the ARMin is the vertical shoulder rotation. Therefore, the exoskeleton robot does not restrict the vertical motion of shoulder complex of the robot user. This motion is not included in any of the other exoskeleton robots. The ARMin has a semi-exoskeletal structure and is equipped with position and force sensors. The semi-exoskeleton structure of the ARMin allows easy adaptation to different patient sizes. Internal/external shoulder rotation is achieved by a special custom-made upper-arm rotary module that is connected to the upper-arm via an orthotic shell. For easy access of the patient's arm, the module is made out of two half cylinders.

E. Mechanical Design with Parallel Manipulators, [26]

Gupta and O'Malley [26] has developed 5DOF haptic arm exoskeleton robot shown in Fig. 5(a) for robot-assisted rehabilitation and training. It uses parallel manipulators and generates the motions of elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and radial/ ulnar deviation. The originality of the exoskeleton is the application of the parallel manipulators. In the mechanical design, it uses 3-RPS platform in the wrist joint [26]. The exoskeleton is comprised of a revolute joint at the elbow, a revolute joint for forearm rotation and a 3-RPS serial-in-parallel wrist. This platform has 3DOF, with actuated prismatic joints. The height of the platform allows for adjustment to forearms of different users and is kept constant during operation. Hardware stops in conjunction with software limits have been used to ensure user safety.

F. Mechanical Design of Wrist Axes Offset: W-EXOS [18]

Figure 5(b) shows the W-EXOS. It has been developed to assist the motions of forearm supination/pronation, wrist flexion/extension and radial/ulnar deviation by Gopura and Kiguchi [18]. The original feature of the design is that it has considered about the axes offset of wrist joint which was not considered in any other design. Therefore, undesired pain of the user's wrist joint can be avoided. In addition, the hand-robot interface has been designed not to disturb the finger motions. The axes offset of wrist joint is important for the wrist joint of the exoskeleton robot, since the wrist joint is sensitive to changes in position and torque. In the design of the W-EXOS, mainly safety is considered in two ways: safety features installed in the mechanical design and safety features inbuilt in control program. Mechanical stoppers are attached for each motion to prevent the exceeding of the movable range. The maximum torque and velocity of the exoskeleton robot is limited by the control program to prevent sudden unexpected motion.

By using the concepts in [17] and W-EXOS, a 6DOF exoskeleton robot (SUEFUL-6) have been developed [19] to assist upper-limb motions. It applied wrist axes offset [18] and mechanism of CR of shoulder joint [17].

G. Mechanical Design with Pneumatic Actuators: Active Support Splint (ASSIST) [53]

A light weight 1DOF exoskeleton robot [see Fig. 5(c)] which is driven by pneumatic soft actuators has been developed and named as active support splint (ASSIST) by Sasaki *et al.* [53]. The main advantage of the device is relieving of the restrained feeling when the device is not operated. It is obtained by the plastic interface with rotary type soft actuators. The ASSIST can be used to assist the wrist flexion/extension motion of elderly or physically weak people. The shape of appliance has decided referring a shape of extension splint for a disabled person. Two cylindrical plastics are attached to the both sides of the palm and arm in order to fix the actuators.

H. Mechanical Design of Exoskeleton for Hand and Fingers Motions [24]

Kawasaki *et al.* [24] have designed an exoskeleton with 18DOF for rehabilitation therapy. The robot is shown in Fig. 5(d). It is designed to support the flexion/extension and abduction/adduction motions of fingers and thumb independently as well as the opposability of the thumb. Moreover, it is designed to support a combination motion of the hand and the wrist. The patient's impaired hand, wearing a glove, is placed on the hand-holding part and is fixed by Velcro straps attached to the finger fixture. The original characteristics of the system are the finger motion assist mechanism and thumb opposability mechanism. A robotic device assisting thumb opposition has never been addressed. The system can use for rehabilitation therapy of fingers, especially thumb independently and opposability, wrist flexion/extension and forearm supination/pronation by patient self-motion control. A finger motion assist mechanism is constructed as an exoskeleton of a finger. This mechanism assists the flexion/extension of the MP and PIP joints and the abduction/adduction of the MP joint. Safety issues are addressed by this robot by including emergency stops buttons for both the operator and the patient. Also periodic sensor fault detection and status supervision of all joint angles and joint torques increase the safety. In addition, output limiting facility added to the motor driver and sub CPU which watches performance of control CPU enhance the safety of the system.

I. Hand Mentor [56]

The hand mentor [56] is the first commercial hand rehabilitation therapy system produced by Columbia Scientific LLC. 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 the compliant air muscle actuator. The device incorporates surface electromyography (EMG) recording electrodes in contact with the patient's muscles and an EMG level display.

J. NEUROexos [58]

A bioinspired three joints-three links robotic arm (NEUROexos) is under development [58]. Main idea of this robot is for implementing bioinspired control strategies and for obtaining a human-like robotic arm to be used for assessing active exoskeletons in fully safe conditions. The robotic system has been deeply coupled to the human user and the exoskeleton design is based on the human model in terms of biomechanics, and control and learning strategies.

K. Other Recent Exoskeleton Designs

A "muscle suit" has been proposed by Kobayashi and Hiramatsu [50] to provide muscular support for the paralyzed or those who are unable to move by themselves. The muscle suit is a garment without a metal frame and uses McKibben actuators driven by compressed air. Since the actuators are sewn into the garment, metal frames have not been used. The muscle suit is helpful for both muscular and emotional support.

Hand Wrist Assisting Robotic Device (HWARD) was developed by Cramer *et al.* in 2007 [51]. It is a 3DOF device that exercises flexion and extension of the hand as well as some wrist movement. 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. The HWARD is a pneumatic actuated desk mounted exoskeleton that supports the patients arm and is attached on the thumb and fingers. It can flex or extend all 4 fingers together about the MCP joint, the thumb at the MCP joint and the wrist. Joint angle sensors in the structure are used to measure the movement of the exoskeleton's joints, and hence, movement of the patient's limbs.

The L-EXOS is an upper-limb exoskeleton robot for haptic interaction in virtual environment [27], [57]. It is a tendon driven wearable haptic interface with four active DOF. The robot can generate the motions of shoulder abduction/adduction, internal/external rotation, horizontal flexion/extension and elbow flexion/extension. The solution of adopting a closed circular bearing has been replaced with an open circular component [27]. A high level of integration with the axis joint has been addressed to fully pursue the weight reduction.

Wege and Hommel [33] designed a hand exoskeleton to accomplish requirements of medical applications. It has included all 4DOF of one finger. The device can be easily attached and also be adjusted to deformed and scarred hands.

A design of a 2DOF exoskeletal mechanism for the lateral and frontal abduction of human upper limb has been proposed in [20]. Major consideration of the design was on the location of the center of rotation of the humerous with respect to the scapula. The motion of the center of rotation of the shoulder has been obtained using a Geneva mechanism.

VII. CONCLUSION

Exoskeleton robots are supposed to play an important role in the field of rehabilitation, motion assist, human power augmentation and haptic interaction. So far, several upper-limb exoskeleton robots have been developed for various purposes. They have their own merits and demerits. This paper reviewed mechanical designs of recent active upper-limb exoskeleton robots. Developing a proper upper-limb exoskeleton robot has been a challenging task, because of the challenges imposed by human upper-limb anatomy, specially the shoulder complex. Requirements, design challenges and the evaluation methods of mechanical designs of an active upper-limb exoskeleton robot were also discussed. In addition, recent upper-limb exoskeleton robots were classified based on actuators used in their mechanical designs.

Some requirements of mechanical designs of active upper-limb exoskeleton robot are still to be fulfilled. Those are especially concentrated in the shoulder mechanism and wrist joint mechanism. It is not easy to assist 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 be biomechanically investigated. Lightweight and efficient power supplies, actuators and transmissions are essential to develop upper-limb exoskeleton robots. Since the exoskeleton robots directly attached to the human body the safety should be considered very carefully.

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