CHAPTER 4

Upper Limb Wearable Exoskeleton Systems for Rehabilitation: State of the Art Review and a Case Study of the EXO-UL8—Dual-Arm Exoskeleton System

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4.1 Background Information on Upper Limb Stroke Rehabilitation

As one of the leading causes of severe long-term disability [1], stroke (ischemic and hemorrhagic) results in 795 K new patients every year (16.9 M worldwide) in addition to the existing 6.6 M stroke patients (33 M worldwide). Hemiparesis (one-sided weakness) or hemiplegia (one-sided paralysis) frequently occurs with spasticity (stiff or tight muscles) and joint/muscle coupling affects 80% of stroke victims. The specific functionality and severity depend on the brain trauma position and size. The patients' participation in activities of daily living (ADLs) is affected, creating a burden on themselves, their families, and society [2]. Of particular interest is that movement capabilities of stroke patients are normally more severely affected on one side, depending on which brain hemisphere has trauma. The bilateral training mode discussed later is based on this observation.

Many poststroke patients are able to regain some capabilities after rehabilitation training. However, due to the limitation of time/skills of human physical therapists, stroke survivors often do not receive sufficient training and do not recover the capabilities they should. Rehabilitation robots, which always have contact with the human's body and are thus "wearable," have the potential to automate the training process and increase the exercise dose while reducing the service cost. As average life expectancy is lengthened by improved medical treatment, the absolute amount of stroke survivors is increasing and rehabilitation wearables are expected to have a promising market.

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In general, rehabilitation wearables can be categorized based on the body parts to be trained: hand and fingers, upper limbs, and lower limbs. Wearables in each category must meet different challenges: devices for hand and fingers require fine movement with low torque output; robots for upper limbs address different symptoms including weakness, spasticity, and/or limited range of motion; and lower limb training devices could focus on balance or energy utilization efficiency. While the wearables for lower limb rehabilitation have gained significant attention in recovering locomotion abilities [3,4], upper limb rehabilitation training devices should receive at least equal attention as participation in ADLs is greatly dependent on upper limb capabilities.

4.2 State of the Art in Upper Limb Rehabilitation Wearables

Our review, in this part, focuses on upper limb rehabilitation wearables excluding standalone hand exoskeletons. These devices are summarized in Tables 4.1 and 4.2.

Early upper limb rehabilitation wearables were based on end-effector robots that transmit forces and torques to patients at the contact point. Since the 1990s, numerous clinical trials have been conducted on end-effector upper limb rehabilitation wearables indicating improved treatment outcomes when compared to traditional therapy [5–9]. Following these successes, upper limb robotic rehabilitation systems have gained acceptance and naturally evolved from end-effector robots, to single-arm exoskeletons, to dual-arm and full-body exoskeletons.

The MIT-MANUS [10–13], commercialized as the InMotionArm (Interactive Motion Technologies, Inc., Cambridge, MA, United States), is a direct-drive five bar–linkage SCARA robot. The robot is attached to the patient's forearm and produces horizontal planar translations. Additional attachments have been developed to enable active control of forearm pronation/supination, wrist flexion/extension, and wrist abduction/adduction. The system is used with robotic therapy games to motivate and coordinate therapeutic tasks, a strategy adopted by the majority of upper limb robotic rehabilitation systems.

The upper limb motion assist system developed by AIST [14] and NeReBot [15] maneuvers the patient's arm by changing the lengths of three cables suspending orthoses/splints worn by the patient. The upper limb mobile assist system by AIST consists of two such orthoses placed on the forearm near the elbow and the wrist. By changing the positions of both orthoses, two rotations and three translations of the forearm can be controlled. The NeReBot is a cable-driven robot featuring a single splint attached to the entire forearm actuated by three motors.

The GENTLE/s [16] and ACT^{3D} [17] both feature a HapticMaster robot [18] connected with a forearm orthosis. The HapticMaster enables each device three active translational degrees of freedom (DOFs) of the forearm. The GENTLE/s system also features a passive elbow orthosis suspended from above by cables for gravity compensation. The ACT^{3D} provides adjustable active gravity compensation.

Table 4.1: Existing upper limb wearables.

Device	Use	Mechanical Design	Control Method	Active (Passive) DOF					
				T	S	E	F	W	H
Dynamometers									
Biodex System 4 Pro [23]	R, TR	Actuated by an electric motor	Isokinetic resistance mode, eccentric mode, passive motion mode, isometric mode, isotonic mode, or position control	1	–	–	–	–	–
HUMAC NORM [24]	R, TR	Actuated by a brushless motor	Isometric testing, isokinetic testing, passive mode, isometric mode, isokinetic mode, or isotonic mode.	1	–	–	–	–	–
End-Effector Robots									
MIT-MANUS [10–13]	R	Actuated by brushless DC motors	Impedance control, EMG trigger	2 +3	0	0	2 +1	0 +2	0
Upper limb motion assist system by AIST [14]	A	Actuated by DC servo motors with pulleys	Position control or velocity control	5	0	0	5	0	0
GENTLE/s [16,18]	R, HF	Actuated by brushed DC motors with antibacklash lead screw spindles	Position, impedance, or admittance control	3 (4)	0	(1)	3 (3)	0	0
ACT^{3D} [17,18]	R, HF	Actuated by brushed DC motors with antibacklash lead screw spindles	Force control	3 (3)	0	0	3 (3)	0	0
NeReBot [15]	R	Actuated by brushless motors with cable transmissions	Position control	3	0	0	3	0	0
iPAM System [19]	R	Pneumatically actuated	Admittance control	6 (6)	3 (3)	0	3 (1)	(2)	0
Bi-Manu-Track [20]	R	Actuated by electric motors	Impedance control	1 (1) × 2	0	0	1 or (1) × 2	(1) or 1 × 2	0
MIME [21]	R	Actuated by servo motors	Position control	6 × 2	0	0	6 × 2	0	0
KINARM [22]	R			2 × 2	1	1	0	0	0

(*Continued*)

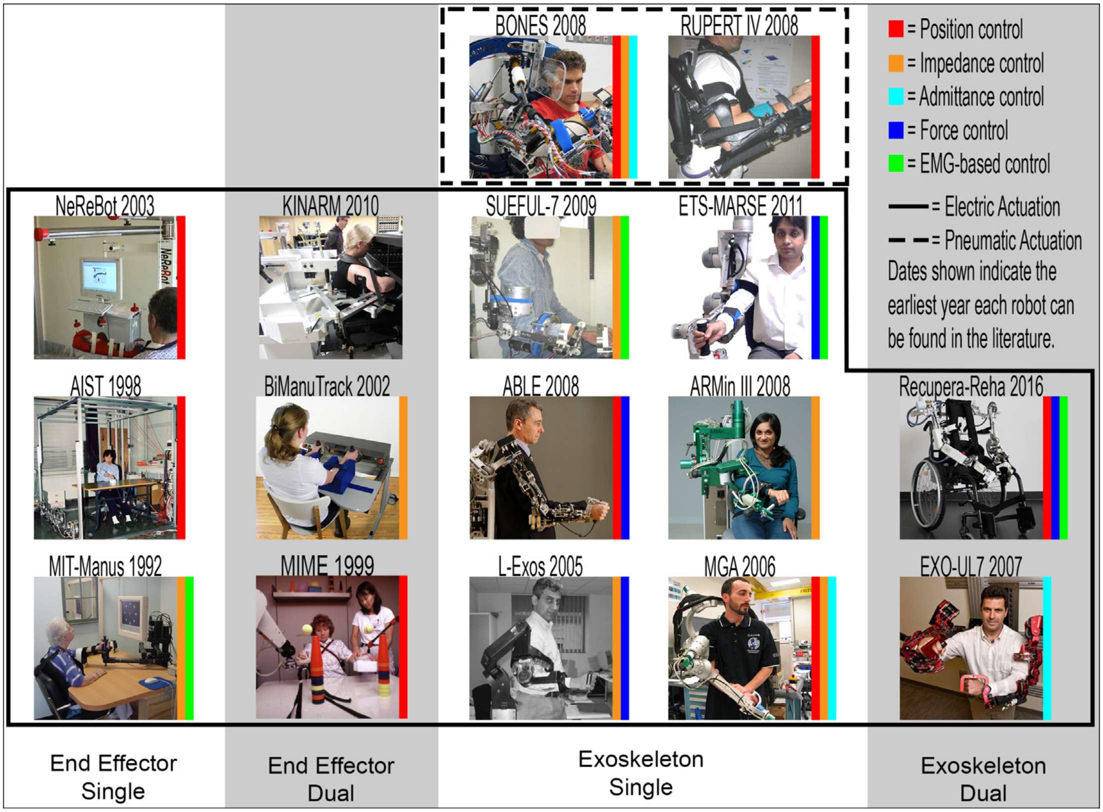
Table 4.1: (Continued)

Device	Use	Mechanical Design	Control Method	Active (Passive) DOF					
				T	S	E	F	W	H
Single-Arm Exoskeletons									
MULOS [29]	A	Actuated by electric motors with cable transmissions, bevel gearboxes, and timing belts	Velocity or force control	5	3	1	1	0	0
L-Exos[31–33]	R, HF	Actuated by permanent magnet DC motors with tendon transmissions	Impedance or direct force control	4 (1)	3	1	(1) − (1) +1	0	0 +2
SARCOS Master Arm [25,26]	TO	Hydraulically actuated	Impedance control. Local control of each joint.	10	3	1	1	2	3
SRE [46]	R	Actuated by braided pneumatic muscle actuators	Joint position control, joint torque control, or impedance control	7	3	1	1	2	0
MEDARM [43]	R	Actuated by electric motors with cable-driven transmissions and timing belts		6	5	1	0	0	0
IntelliArm [41,42]	R	Actuated by servomotors	"Intelligent stretch," "back-drivable," "assistive," or "resistive"	8 (2)	4 (2)	1	1	1 (2)	1
RUPERT IV [47,48]	R	Actuated by pneumatic muscle actuators	PID-based feedback, iterative learning controller-based feedforward control	5	2	1	1	1	0
BONES [34–36]	R	Actuated by pneumatic cylinder actuators	Model-based adaptive control	4 +2	3	1	0 +1	0 +1	0
ABLE [37,38]	R, A, TO, HF	Actuated by DC motors with screw-and-cable transmissions	Hybrid force-position control	7	3	1	1	2	0
ARMin III [39]	R	Actuated by brushed DC motors with harmonic drive transmissions	Impedance control	4 +2	3	1	0 +1	0 +1	0
MGA [40]	R	Actuated by brushless DC motors with harmonic drive transmissions	"Composite" control groups joints. Each group can use impedance, admittance, or position control.	5 (1)	4	1	(1)	0	0

SUEFUL-7 [30]	A	Actuated by motors with pulleys, cable drives, spur gears, and bevel gears	Muscle-model-oriented EMG-based impedance control	7	3	1	1	2	0
RehaBot [49]	R	Actuated by serial elastic actuators and direct-drive motors	Force control	7	3	1	1	2	0
Exorn [44,45]	R, A	Actuated by DC geared and brushless DC servo motors	Position control or EMG-based control	10	6	1	1	2	0
ETS-MARSE [50]	R	Actuated by brushless DC motors with harmonic drive transmissions	Computed torque control or EMG-based control	7	3	1	1	2	0
Dual-Arm Exoskeletons									
EMY [52]	BMI	Actuated by brushed DC motors with screw-cable-systems and gearboxes	Position, velocity, or torque control	8	2 ×2	1 ×2	1 ×2	0	0
CAPIO [53]	HF, TO	Actuated by serial elastic actuators	Zero force, inverse dynamic, force feedback, or determinate force control	20 (4)	3 (1) ×2	2 ×2	1 ×2	2 ×2	0
Recupera-Reha [54]	R	Actuated by brushless DC motors, servo motors, and serial elastic actuators	Position, torque, or EMG/EEG-based control	12 (2)	3 ×2	1 ×2	1 ×2	(1) ×2	1 ×2

Use: R, rehabilitation; A, motion assistance; HF, haptic feedback; P, power augmentation; TO, teleoperation; BMI, evaluation of BMI; TR, training (athletic/strength). DOF: T, total; S, shoulder; E, elbow; F, forearm; W, wrist; H, hand; +/−, DOFs of optional attachments; ×2 for dual arm device.

Table 4.2: Graphical summary of existing upper limb rehabilitation robots.



The iPAM system [19] features two rigid 3D robot arms connected to the patient at the upper arm and wrist. The system can therefore actively control the positions of upper arm and forearm, but both connection points passively permit all orientation DOFs.

Bi-Manu-Track [20], MIME [21], and KINARM [22] are dual-arm robotic systems and are thus capable of bimanual therapy, a desirable feature that is not achievable with a single-arm system. Bi-Manu-Track is a portable reconfigurable device limited to one active and one passive DOF between forearm pronation/supination and wrist flexion/extension. MIME consists of 6-DOF Puma-560 robots and position digitizers attached at each forearm. KINARM is a planar device that mechanically supports the weight of the arm while actuating two-DOF horizontal motions.

An additional notable class of rehabilitation robot that can be used for the upper limbs is the dynamometer. Dynamometers such as the Biodex System 4 Pro [23] and the HUMAC NORM [24] feature a single motor that can be repositioned and connected to various attachments to target specific motions.

End-effector robots have been shown to be effective in rehabilitation, and several have even found commercial success. However, these robots suffer from several critical limitations.

End-effector robots typically have significantly reduced ranges of motion when compared to the human arm. For the workspace of an end-effector robot to encompass the workspace of the human arm, the robot must be very large because the base of the robot must be outside of the reach of the arm to prevent collisions. In addition, the robot would need to reach each part of the workspace of the human arm without physically overlapping with the user.

End effectors move individual points of the human arm. The human arm is a redundant manipulator with seven DOFs, so controlling position and/or orientation of a point on the arm does not control the configuration of the entire arm. Consequently, it is challenging for an end-effector rehabilitation robot to target a specific joint motion for therapy. To the best of the authors' knowledge, there is no end-effector rehabilitation robot that can determine and control all of the DOFs of the human arm.

To circumvent these and other limitations, a large number of upper limb exoskeleton robots have been developed. Upper limb exoskeletons are structured in an anthropometric fashion that supports the partial/full range of motion of the human arm. They are designed to be worn by the user, and are attached at multiple locations. Although this can significantly complicate the design of the robot, it enables much larger ranges of motion and the ability to target specific joint motions for therapy. Exoskeletons can broadly be categorized by application, number of DOFs, and whether the exoskeleton is worn on one or both arms.

The SARCOS Master Arm [25,26] and SAM [27,28] are single-arm exoskeletons designed for teleoperation. The Sarcos Master Arm and SAM have the seven main DOFs of the human arm: shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension, forearm pronation/supination, wrist flexion/extension, and wrist abduction/adduction. SAM is a wearable portable system, weighing just 7 kg.

MULOS [29] uses cable transmissions at the shoulder joints, a bevel gearbox at the elbow, and a timing belt at the forearm. SUEFUL-7 [30] features offset centers of rotation at the wrist to match the slightly offset joint axes of the wrist and a moving center of rotation at the shoulder joint to more accurately match movements of the shoulder. These systems are designed to provide assistance with ADLs.

L-Exos [31–33] has a passive forearm DOF, but an attachment makes it active and adds two hand DOFs (thumb and forefinger). L-Exos can apply a 100 N force on the palm in any direction enabling its use as a haptic feedback device for virtual reality (VR). BONES [34–36] uses a parallel mechanism for a spherical joint at the shoulder and a serially placed actuator for the elbow DOF. An attachment can add the forearm DOF and wrist flexion/

extension. ABLE [37,38] features screw-and-cable transmission systems that enable the motor to be placed along the limb parallel to the cable. This permits ABLE to have a highly compact design compared to systems with transversal motors or beveled gearboxes.

In order to account for the human shoulder not being a perfect spherical joint, several exoskeletons have been designed with additional or offset shoulder DOFs. ARMin III [39] couples the shoulder elevation angle with a vertical translation of the shoulder, and has an attachable active forearm pronation/supination and wrist flexion/extension module. MGA [40] has an extra vertical translation shoulder DOF. IntelliArm [41,42] has not only the added active vertical translation and but also two passive horizontal translation shoulder DOFs. MEDARM [43] replaces the standard three-DOF shoulder mechanism with two rotational DOFs at the sternoclavicular joint and three rotational DOFs at the glenohumeral joint. Exorn [44,45] is a portable exoskeleton designed to have all the DOFs of the human arm including two at the shoulder girdle and four at the glenohumeral joint.

SRE [46] is a seven-DOF rehabilitation exoskeleton that has a singularity when the arm is parallel to the ground due to the shoulder joint design. RUPERT IV [47,48] is a five-DOF portable exoskeleton. RehaBot [49] is a commercially developed upper limb exoskeleton that is part of a larger rehabilitation system. ETS-MARSE [50] is a rehabilitation exoskeleton designed for use with electromyography (EMG)-based control.

The earlier single-arm exoskeletons feature a wide range of designs with varying complexities targeting various joints. However, single-arm exoskeletons are inherently incapable of performing tasks requiring coordination between both arms. More importantly, bilateral movement training has been shown to be more effective in specific aspects of stroke rehabilitation than unilateral movement training [51]. To perform bilateral actions, it is therefore necessary to use a dual-arm exoskeleton. Due in part to the complexity of dual-arm systems, they tend to be more recently developed, and there are far fewer, compared to single-arm exoskeletons.

EMY [52] is a dual-arm exoskeleton with active DOFs of shoulder internal/external rotation, shoulder flexion/extension, elbow flexion/extension, and forearm pronation/supination. It features the same screw-cable-system for actuation that ABLE uses. The forearm DOF is achieved by a parallel structure of three rods on ball-joints connecting a rotating arch to a fixed arch. EMY is designed specifically for the evaluation of Brain Machine Interface.

CAPIO [53] is a dual-arm exoskeleton with 20 active DOFs, including four on the back and an extra translational DOF at each elbow. CAPIO uses serial elastic actuators and is designed for use as a haptic feedback device and teleoperation.

The modular upper limb portion of the full-body Recupera-Reha [54] system is a recent dual-arm exoskeleton designed for stroke rehabilitation. It has six active DOFs, including one for hand grasp, and one passive DOF for wrist flexion/extension for each arm. The shoulder mechanism uses brushless DC motors, while the elbow and forearm DOFs are actuated by two different custom serial elastic actuators.

4.3 Dual Arm Exoskeleton System EXO-UL8 Case Study

Clinical trials in stroke rehabilitation training bring inspiration to features of new rehabilitation robots. One promising training protocol is the so-called "mirror-image" bilateral training [55], during which the patient moves his/her healthy arm and unhealthy arm simultaneously. This training method may accelerate the recovery of poststroke motor capability as bilateral mirror movements are thought to stimulate the crosstalk between two brain hemispheres. While it is difficult for traditional physical therapists to simultaneously control both arms of a patient in the same movement pattern, multi-DOF powered exoskeletons are intrinsically capable of doing the task. Among the many exoskeletons with a multi-DOF feature on one arm, a few have expanded the design to a symmetric, dual-arm system (Table 4.1). The "EXO-UL8," a dual arm exoskeleton system developed by Bionics Lab, University of California Los Angeles (UCLA), is the fourth generation in this upper limb rehabilitation exoskeleton robot series (Fig. 4.1). It is also the second generation that comes with two arms. In EXO-UL8, contact forces are measured by force sensors placed between the braces (upper arm, forearm, palm, and fingers) and the exoskeleton structure. Joint angles are measured by encoders located on the shafts of the joints. Two PCs connected via UDP are dedicated to low-level real-time control, VR rendering, and data collection.

4.3.1 Mechanical Design

According to the possible efficiency of bilateral rehabilitation training, since the third generation, the system has two arms facilitating unilateral and bilateral training modes. In this section, we focus on the features of either side of the system. The coupling between two arms will be discussed in the Section 4.3.2.

4.3.1.1 Range of motion

The EXO-UL8, like its predecessor, was kinetically designed to overlap with 99% of a healthy human arm workspace (Fig. 4.2). The shoulder joint was designed to eliminate singular configurations within the workspace and was repositioned at the edge of the arm workspace [56]. Single-DOF hand grippers were added to increase the total number of DOFs to 8 for each arm and to enable reach-and-grasp motions that are critical to the recovery of the motor control system following stroke [57–60]. Furthermore, each link is adjustable in length in a telescopic fashion to accommodate a wide range of anthropometric arm dimensions (5%–95%). Each joint includes mechanical limits to prevent motion beyond anatomical limits.

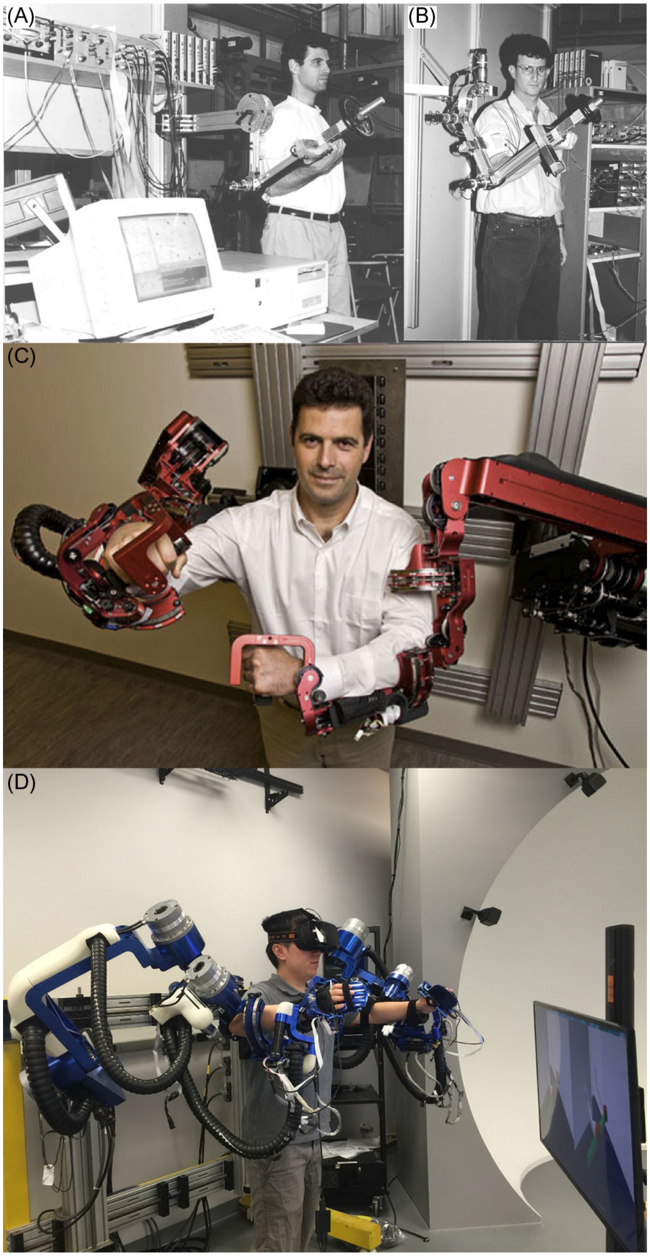


Figure 4.1
Generations of the upper limb exoskeleton system. (A) EXO-UL1, a one-DOF (elbow joint) powered exoskeleton developed as a proof of concept for using myosignals as the primary command signals; (B) EXO-UL3, a three-DOF (two at shoulder, one at elbow) powered exoskeleton; (C) EXO-UL7, a dual-arm powered exoskeleton (cable-driven) with seven DOFs on each arm; (D) EXO-UL8, a dual-arm powered exoskeleton with seven DOFs and a one-DOF haptic gripper on each side, actuated by harmonic motors.

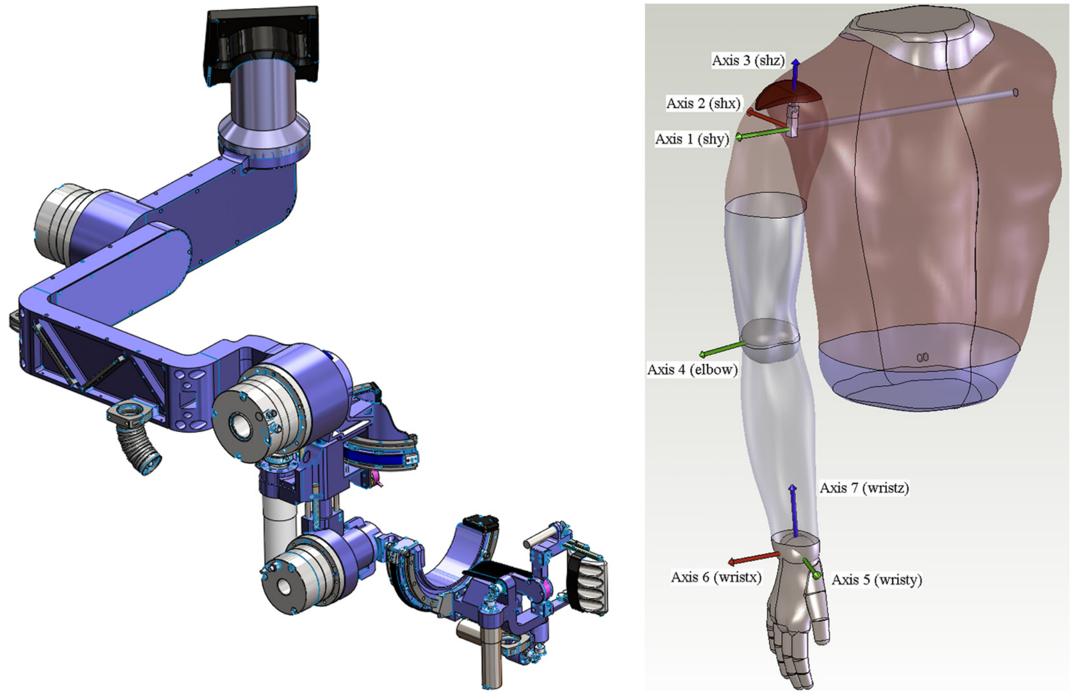


Figure 4.2
The EXO-UL8 and the corresponding DOFs marked on the human arm.

4.3.1.2 Actuation mechanisms

Instead of continuing the cable-driven actuation mechanism in the previous generation (EXO-UL7), the new exoskeleton uses electric drives. There are several reasons for using electric motors, (1) increased torque outputs enable abnormal movement correction as well as gravity compensation; (2) more accurate bottom-layer control can be achieved without unwanted compliance/delay; (3) acceptable torque−volume ratio. For each arm, three harmonic drive (Harmonic Drive Systems, Inc., Japan) servo systems are equipped with encoders and brakes to facilitate movement for the first three DOFs at the shoulder joint and to enable freezing functionality at emergency configurations. The servo systems were sized to support the joint torques developed as a result of the weights of the mechanical arm, the operator's arm as well as a 5 kg payload held by the hand. In addition, the servo systems can produce joint torques that are equivalent in magnitude to the ones produced by a healthy human and they allow the EXO-UL8 to move with the linear and angular velocities recorded in ADLs [2]. Five DC motors (Maxon Motor, Switzerland) are used to realize the five remaining DOFs (one at the elbow, three at the wrist, one at the hand gripper). A set of four force/torque (F/T) sensors are located at the physical interaction points between the human operator and the exoskeleton system: three multiaxis F/T sensors (ATI mini 40) are located on the upper arm, lower arm, and palm, between a brace and the corresponding exoskeleton link; one single-axis force sensor is incorporated into the exoskeleton hand for sensing grasping forces applied by the fingers. Anodized aluminum links are custom made and all cables are covered with 3D-printed carbon fiber–coated shells.

4.3.2 Control Strategies

To realize the seamless integration of human arms and the exoskeleton, a comprehensive controller (Fig. 4.3) was developed including: (1) admittance control, as the foundation of the control approach translating forces applied by the operator arm and hand on the various F/T sensors into joint angle changes [61]; (2) gravity and friction compensation, as a component of the control algorithm that compensates gravity and friction through feedforward-model-based prediction that is fed into the joint torques; (3) swivel prediction (human arm redundancy resolution) that aims to position the elbow joint at an appropriate swivel angle; and (4) other force fields used to provide patients additional assistance during training. To keep the system simple and easy-to-use, no contextual information like EEG or EMG is used and thus the controller is more complex.

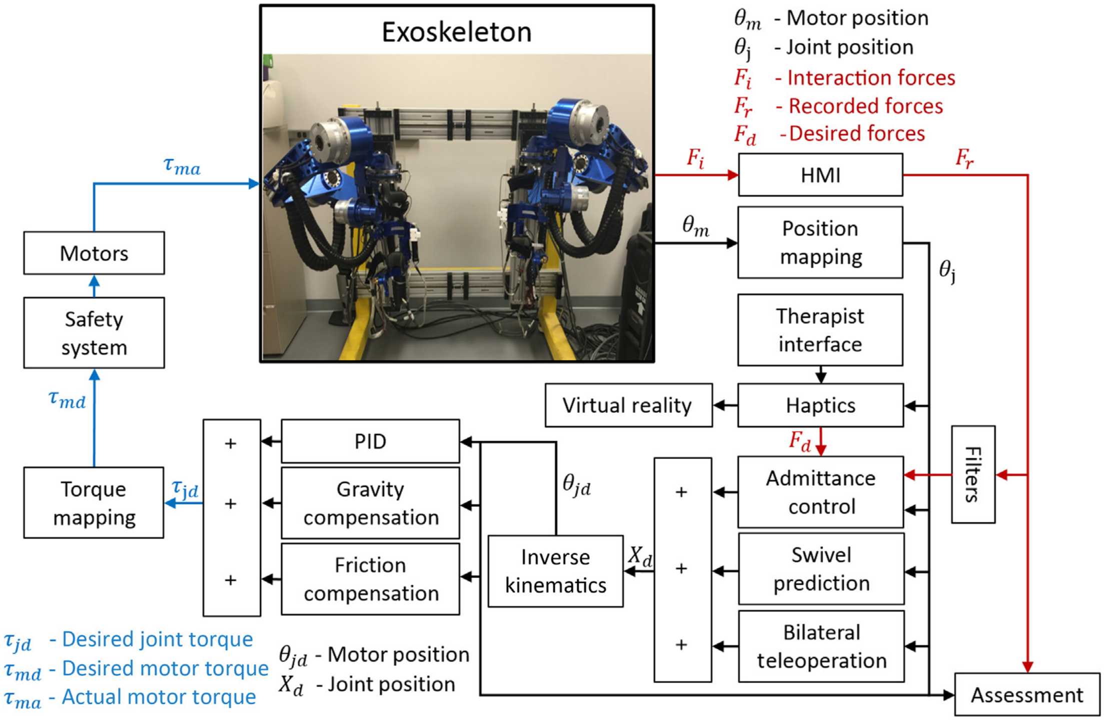


Figure 4.3
Block diagram of the EXO-UL8 controller.

1. Applying Pattern from Human Motion: Admittance Control

   Admittance control in task space is the fundamental servo control scheme of the system. It maps forces and torques applied on the multiaxis F/T sensors located at the contact interface from the operator's arm/hand to the exoskeleton system, and provides linear and angular velocity according to these input commands to the system in a way that aims to set the interaction contact forces and torques to zero [62,63].
2. Assistive Mode: Gravity Compensation

   Among all the elements of the equation of motion (inertia, velocity, gravity), experimental results indicate that during ADL of the human arm and hand gravitational loads are the largest. As such a gravity compensation algorithm is used to compensate the gravitational loads generated at the joint space due to the gravity field. Gravitational loads generated by the weight of the exoskeleton itself as well as of the human operator's arm are fed forward into the control system of the exoskeleton [64].
3. Redundancy Resolution and Joint Synergies

   The human arm with its seven DOFs is considered a redundant system. Therefore it is necessary for the control system to estimate the swivel angle (elbow joint position with respect to an axis connecting the shoulder and wrist). The manipulability ellipsoid-based redundancy resolution criterion provides an estimation of the elbow's swivel angle within an error range of ± 5 degrees (Fig. 4.4) [65]. The approach is further generalized by synthesizing multiple criteria [66]. This feature helps stroke patients in (1) freely using their functional arm to control the exoskeleton with less resistance during bilateral movement training; (2) getting posture correction (unwanted compensation removal) during unilateral movement training. In addition, illustrated in Fig. 4.5, the modeling of joint synergies observed from stroke patients provides a reference in training task trajectory design and interaction force limit calculation [67,68].
4. Force Fields

   Shown in Fig. 4.6, different force fields should be implemented when using different training modes.

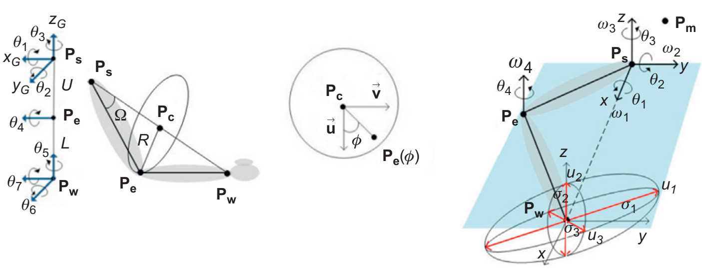


Figure 4.4
Redundancy resolution calculation based on the end-effector's manipulability [65].

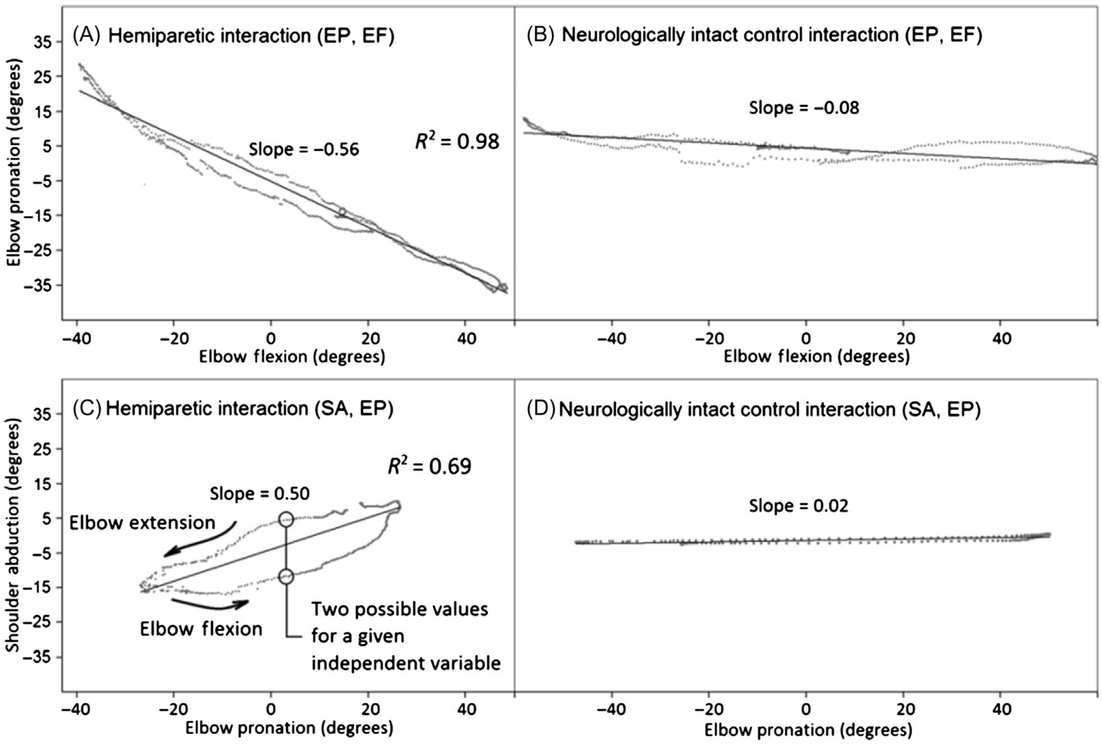


Figure 4.5

Joint synergies observed on a stroke patient (A and C) compared with those on a healthy one (B and D). SA, shoulder abduction; EF, elbow flexion; EP, elbow pronation.

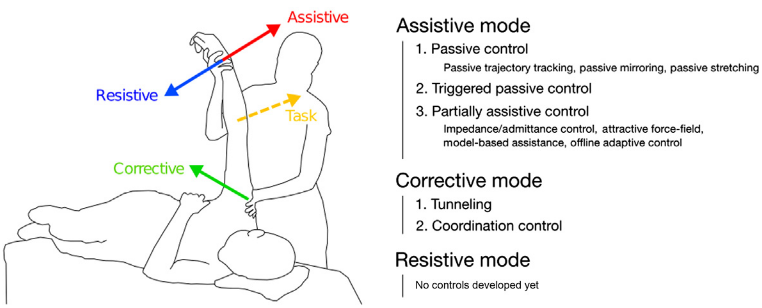


Figure 4.6

Global strategies for robotic-mediated rehabilitation and current implementations on exoskeletons [69].

Force fields are task-specific and implemented as either repulsion or attraction fields within a VR task, or a combination of both. For example, in a reach-to-grasp task while moving along a specific trajectory, an attraction force field is placed on the target, and the trajectory is wrapped with a radial repulsion force field (tunneling) that opposes deviation of the hand from the trajectory.

Our recent pilot study on asymmetric dual-arm training has validated the assistive force functionality on EXO-UL8 [70]. Another theoretical study of ours has introduced the Arm Postural Stability Index (APSI) and shown that resistive forces change the human arm redundancy resolution, thus the controlling strategy could be altered based on magnitude/joint position [71].

5. System Safety

A straightforward approach to ensure system safety is to set limiting thresholds of joint position and its first and second order derivatives with respect to time. In EXO-UL8, a multimodal safety management has been embedded into the system at the hardware, software, and operational levels. As mentioned earlier in mechanical design, the exoskeleton with brakes on all the actuators covers 99% of the joint range of a healthy person, and a subset of that movement range is constrained by rubber stops. Based on the encoder readings, the joint velocity and acceleration are also limited by the controller. In addition to these settings, an enabling pad controlled by the physical therapist and an emergency stop are embedded into the loop to freeze the system at any point in time. A 3 Hz low-pass Butterworth filter is applied to the force processing level in order to eliminate the system instability resulting from a human's unintentional vibration.

4.3.3 Virtual Reality Tasks

Based on ADL, as well as the previously measured daily activity data including the range of motion in each joint of a healthy human [2], a set of 18 VR tasks were developed. The exoskeleton system or a Kinect camera can be used to interact with these tasks in VR. The motivation for these two approaches is that, while patients will only have access to the exoskeleton system during therapeutic sessions in a clinical setting, they could easily utilize a Kinect to do at-home training between appointments. In this way, the treatment is part of a continuum bridging the clinic and home settings. The VR tasks are categorized based on whether the user interacts with static or dynamic VR objects. Furthermore, each category includes diagnostic and treatment tasks utilizing either a single DOF (moving in a single plane) or multiple DOFs (moving in space). A graphical user interface allows the therapist to control key parameters of each task and to set individual levels of difficulty for each patient. The typical parameters that can be changed are locations and size of the interactive objects as well the speed they move in space.

Haptic feedback can be calculated and transferred back to each joint of the exoskeleton based on collision detection. Most of the tasks are designed to be operated in both unilateral and bilateral modes. In the bilateral mode, a patient uses the healthy arm to move the exoskeleton and the same movement is copied to the other side, enabling the disabled arm to realize mirror-image movement; uncoupled bilateral mode is used for advanced asymmetric dual-arm manipulation, such as opening a bottle or folding clothes.

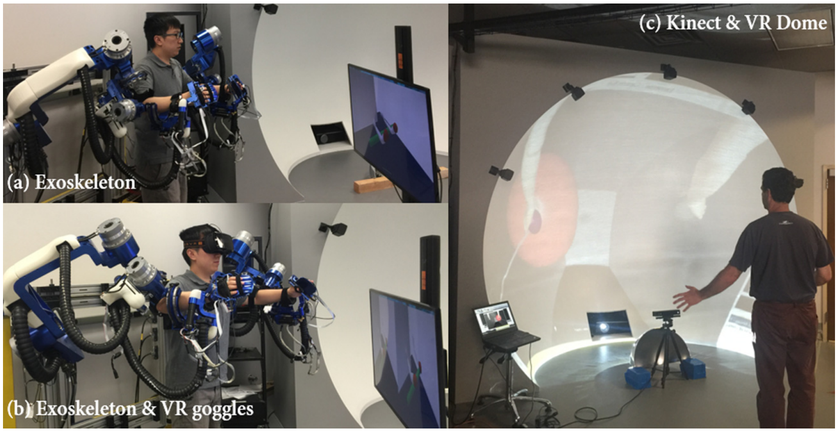


Figure 4.7
Modes of operation in virtual reality: (A) bilateral mode of the exoskeleton; (B) using exoskeleton with VR goggles; (C) using the immersive VR 3D dome with a Kinect v2 camera.

Using the previously mentioned controller, our robotic exoskeleton can train severely impaired patients in different modes including unilateral and bilateral. The coupling between the two arms is further modified to stiff/spring/damping models. Different viewports are used to improve the VR interaction experience, including a head mounted device with a 100-degree field of view and an immersive 3D dome (Fig. 4.7).

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