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Review on Design and Control Aspects of Robotic Shoulder Rehabilitation Orthoses

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Abstract

Robotic rehabilitation devices are more frequently used for the physical therapy of people with upper limb weakness, which is the most common type of stroke-induced disability. Rehabilitation robots can provide customized, prolonged, intensive, and repetitive training sessions for patients with neurological impairments. In most cases, the robotic exoskeletons have to be aligned with the human joints and provide natural arm movements. This is a challenging task to achieve for one of the most biomechanically complex joints of human body, i.e., the shoulder. Therefore, specific considerations have been made in the development of various existing robotic shoulder rehabilitation orthoses. Different types of actuation, degrees of freedom (DOFs), and control strategies have been utilized for the development of these shoulder rehabilitation orthoses. This paper presents a comprehensive review of these shoulder rehabilitation orthoses. Recent advancements in the mechanism design, their advantages and disadvantages, overview of hardware, actuation system, and power transmission are discussed in detail with the emphasis on the assisted DOFs for shoulder motion. A brief overview of control techniques and clinical studies conducted with the developed robotic shoulder orthoses is also presented. Finally, current challenges and directions of future development for robotic shoulder rehabilitation orthoses are provided at the end of this paper.

Keywords

review, control, design, aspects, orthoses, robotic, shoulder, rehabilitation

Disciplines

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Review on Design and Control Aspects of Robotic Shoulder Rehabilitation Orthoses

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Abstract— Robotic rehabilitation devices are more frequently used for the physical therapy of people with upper limb weakness which is the most common type of stroke-induced disability. Rehabilitation robots can provide customized, prolonged, intensive and repetitive training sessions for patients with neurological impairments. In most cases, the robotic exoskeletons have to be aligned with the human joints and provide natural arm movements. This is a challenging task to achieve for one of the most biomechanically complex joint of human body, the shoulder. Therefore, specific considerations have been made in the development of various existing robotic shoulder rehabilitation orthoses. Different types of actuation, degrees of freedom (DOFs) and control strategies have been utilized for the development of these shoulder rehabilitation orthoses. This paper presents a comprehensive review of these shoulder rehabilitation orthoses. Recent advancements in the mechanism design, their advantages and disadvantages, overview of hardware, actuation system and power transmission are discussed in detail with the emphasis on the assisted DOFs for shoulder motion. A brief overview of control techniques and clinical studies conducted with the developed robotic shoulder orthoses is also presented. Finally, current challenges and directions of future development for robotic shoulder rehabilitation orthoses are provided at the end of the paper.

Index Terms—stroke, shoulder rehabilitation, robotic orthoses, exoskeleton, mechanism design, actuation, control strategies.

I. INTRODUCTION

THE proper functionality of shoulder is crucial for effective use of human arm during activities of daily living (ADL). Unfortunately, the weakness and loss of upper limb motor control is a common neurological impairment arising from stroke, with 88% [1] (77.4% [2]) of stroke survivors running into some degree of functional limitations of upper limb. The exhausting and laborious conventional physical therapies are initiated in clinics to maximize potential for motor recovery [3-5]. Moreover, the intricate anatomy of upper limb makes its recovery more complex in comparison to lower-limb rehabilitation.

However, recent developments in technology enabled robotic devices to assist stroke patients with upper limb disabilities. These robotic devices can provide task oriented,

prolonged, accessible, repetitive and intensive physical therapy [6-9]. Therefore, these upper limb rehabilitation robots have made it possible to improve the motor recovery in stroke survivors while reducing the burden on physical therapists [8, 9].

Upper limb rehabilitation robots [10-16] can be divided into two types: *exoskeletons* or *orthotic systems* where the robot's joints are designed to correspond with the human joints and *end-effector based devices* that are connected to the arm segment at one point with the axes that are usually not aligned with the joints of the subject. Compared with end-effector based robots, exoskeletons are more complex in terms of mechanism design and actuation as well as control. The adjustability of robotic orthoses to human body is more difficult and can cause joint axes misalignments which in turn lead to undesirable interaction torques. This is a challenging task to consider when designing robotic orthosis for the shoulder complex, which is composed of several bones and can perform complex motions with various degrees of freedom (DOFs). Numerous groups of researchers have designed and built different robotic devices with various mechanical advancements for shoulder complex rehabilitation.

The purpose of this paper is to review the design and control aspects of existing robotic orthoses for shoulder rehabilitation and to discuss some areas for future development. To limit the scope of this work, the passive robotic orthoses for shoulder rehabilitation (such as WREX [17] and Dampace [18]) and the end-effector-based robotic devices developed for shoulder rehabilitation (e.g. MIT-MANUS [19]) are not included in this review. Moreover, although most of the upper limb exoskeletons reviewed in this paper also assist other parts of arm such as elbow, forearm and wrist, the discussion of these upper limb segments is excluded from this review. To increase the reliability of the reviewed papers only papers published in peer review journals and highly cited or selected recent conference papers are considered in this paper.

II. BIOMECHANICS OF SHOULDER COMPLEX

The biomechanics of shoulder complex, well studied and described in the literature [20-25], is briefly presented in this section since the knowledge of the anatomy and the movement characteristics of shoulder is an essential step towards the development of robotic shoulder rehabilitation orthoses.

The human shoulder shown in Fig. 1 is an integrated complex with three bones (clavicle, scapula and humerus) and

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four independent joints. The sternoclavicular (SC) joint connects the clavicle to the thorax, the acromioclavicular (AC) joint connects the scapula to the clavicle, the scapulothoracic (ST) articulation describes scapula motion over the thorax and the glenohumeral (GH) joint, also referred as shoulder joint, connects the humerus to the scapula. The former three joints compose the closed-kinematic chain called shoulder girdle. The glenohumeral joint is commonly oversimplified as a “ball and socket type” joint with three DOFs. It is formed by the “socket” of the female part of the scapula, also called glenoid cavity, and the upper part of the humerus, named humeral head (HH).

The integrated motion between scapulothoracic and glenohumeral joint, which results in the displacement of the humerus, is usually referred as scapulohumeral (SH) rhythm or shoulder rhythm [26, 27]. Therefore, the position of the centre of glenohumeral (CGH) joint, also referred as instantaneous centre of rotation (ICR) of the shoulder joint, is dynamic and it shifts due to interactions with the shoulder girdle [28]. Moreover, there are also individual differences in anatomical characteristics and joint kinematics.

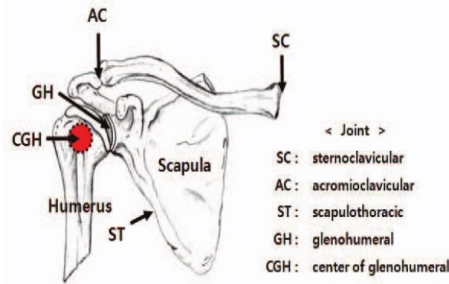


Fig. 1. Structure of shoulder complex [29].

SHOULDER	flexion (+) extension (-)	abduction (+) adduction (-)	(+) internal rotation (-) external rotation
	ROM -50° ~ 180°	0° ~ 180°	-90° ~ 90°
SHOULDER GIRDLE	elevation (+) depression (-)	protraction (+) retraction (-)	
	ROM -10° ~ 20°	-20° ~ 20°	

Fig. 2. Movements of shoulder complex [29].

The three rotational movements of the shoulder, shown in the upper part of Fig. 2, can be described with the following terms: flexion/extension (F/E), abduction/adduction (A/A) and internal/external rotation (IR/ER). The shoulder girdle's motion has 4-DOFs overall but is generally described by two translational movements as shown in the lower part of Fig. 2: elevation/depression (E/D) and protraction/retraction (P/R) [30]. Hence, with three rotational and two translational the simplified model of the shoulder complex has 5-DOFs.

III. MECHANISM DESIGN

Since the human shoulder complex is biomechanically ingenious, specific design considerations have to be made when developing robotic shoulder orthoses. In this section, a brief review of the state-of-the-art robotic shoulder rehabilitation orthoses with their mechanism design, number of DOFs for shoulder and actuation types is presented.

A. Robotic Shoulder Orthoses Powered by Electric Actuators

A robotic orthosis ARMin III (Fig. 3(a)) has been developed at the ETH Zurich for upper limb rehabilitation from its previous versions ARMin I [31] and ARMin II [32]. It was the first exoskeleton robot to be commercially available, now known as Armeo Power (Hocoma product), which has been used in several hospitals in Europe and US [33]. ARMin III exoskeleton has 6-DOFs with 3 actuated DOFs for shoulder. The joints (revolute and prismatic) of this heavy back-drivable robotic orthosis with rigid links are actuated by DC motors with harmonic drive (HD) gearbox. The mechanical end stops, spring and laser pointers are used to increase the safety, compensate the weight and ease the patient-positioning, respectively. Furthermore, this robotic device can be easily adjusted from left to right side which makes it operationally efficient in clinics. However, the prismatic joint that lifts the whole structure takes a lot of space and complicates the actuation of the robot. The vertical motion of CGH, which is modeled as a rotational movement without any horizontal translation, is only achievable along with the arm elevation which limits training of some shoulder movements and causes misalignments between the patient and robot axes [34].

On the other hand, the specific shoulder motions in vertical translational direction, limited with ARMin III, can be trained with another 6-DOFs robotic shoulder orthosis called Maryland-Georgetown-Army (MGA) exoskeleton, shown in Fig. 3(b) [39]. The shoulder complex in this robotic device is enclosed with circular rigid links with three revolute joints modelling a “ball-and-socket” joint. Moreover, this exoskeleton is among the first to take scapula motion into account considering shoulder girdle's elevation and depression [36]. However, the use of the additional motor (mounted as other motors directly on joint) that lifts the mechanism upwards could lead to joint axes misalignments and make this non-back-drivable robot more expensive and hazardous.

A robotic 7-DOFs cable-actuated anthropomorphic exoskeleton CADEN-7, shown in Fig. 3(c), has been developed for upper extremities rehabilitation with 3-DOFs for glenohumeral joint in the University of Washington, Seattle [37]. The advantages of this device are low inertia, negligible backlash, high stiffness links, mechanical stops, emergency switches and driven pulleys that make it possible to distantly locate the actuators reducing the torques on the robot framework. The drawback of this actuation system is that it constraints the transportability and adjustability of the exoskeleton. Moreover, the electric motors used to actuate this high power robotic orthosis are heavy. The succeeding two-arm exoskeleton system of CADEN-7 is named EXO-UL7 (developed in USCS) [40].

Another 5-DOF robotic orthosis developed for upper arm

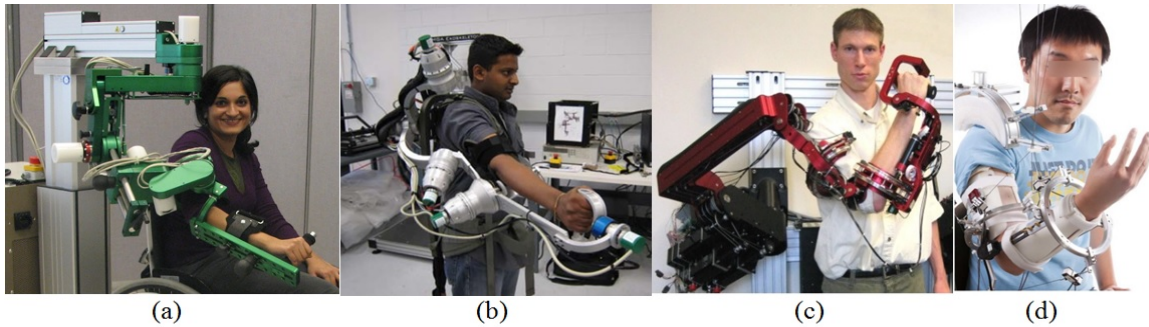


Fig. 3. (a) ARMin III [34], (b) MGA [36], (c) CADEN-7 [37], (d) CAREX [38].

rehabilitation is called Cable-driven ARm EXoskeleton (CAREX) (Fig. 3(d)) [41]. Instead of the rigid links, this robotic orthosis has three lightweight cuffs attached around the shoulder, the upper arm and the forearm, respectively. The limb parts are moved by cables passing through the cuffs that are driven by motors. Four such cables are used for three rotational DOFs of shoulder joint. Due to the use of these cables, the motors are placed away from the human body. This actuation concept was adopted from the wearable haptic device on a human arm [42]. The rotary encoder and sensors in CAREX are used to determine the orientation of glenohumeral joint. The major advantages of this device include a reduced overall weight (1.55 kg) and loads on arm segments. The exoskeleton is not required to be aligned with human joint axes since there are no joints and links. The cables go from one segment of the arm to another without the need for independent sets of cables and there are no restrictions on natural arm movements [38]. An approach for real-time measurement of CGH with CAREX was presented in [43]. Nonetheless, more accurate estimation of the CGH and workspace analysis are still required to establish proper kinematic model.

The IntelliArm is a robotic orthosis that has more DOFs (7 active (*i.e.* actuated) and 2 passive) than most of the exoskeletons for upper limb rehabilitation and can independently and synchronically control the shoulder, elbow, and wrist [44]. In this exoskeleton, all 3-DOFs of shoulder joint and the vertical shift of GH joint are provided with four active DOFs whereas two passive DOF are used for anteroposterior and mediolateral displacement of GH joint. Altogether the use of these active/passive joints can thoroughly replicate the shoulder movements, and the exoskeleton's rotation axes can be aligned with the patient's shoulder taking into account scapular and body movements [45]. Shoulder's reaction torques and forces are measured using a torque/force sensor fixed to the shoulder. The actuation is provided through cable transmission by motors placed remotely from the patient's head. A circular guide and a cable mechanism are used for shoulder's twisting joint (internal/external rotation). Even though this exoskeleton is closely aligned with the shoulder, the heavy and expensive high-torque motors hinder its use in clinical settings [46]. A similar mechanism design with active shoulder girdle control was proposed in [29].

The National Taiwan University Hospital-ARM (NTUH-ARM) is an orthosis with seven actuated DOFs, six of which (1 prismatic and 5 rotational) account for the shoulder. This

redundantly actuated robotic orthosis is powered by using brushed DC motors and assists all five shoulder DOFs [47]. Another electrically actuated compatible 3-DOFs shoulder exoskeleton translates two axes of shoulder joint to adapt the CGH position describing its mechanical motion using the sagittal, frontal, transverse, and rotation (SFTR) system [48].

One of the most advanced mechanism designs for shoulder rehabilitation is presented in MEDARM exoskeleton that fully covers all shoulder rotational and translational motions [49]. However, according to the authors' knowledge, no real prototype of this robotic rehabilitation device with proposed electrical type of actuation system is built. ASSISTON-SE is another proposed exoskeleton for shoulder rehabilitation that has five active DOFs and a passive slider to fully assist all shoulder motions [50]. Another recent exoskeleton with three parallel linear electric actuators (3-DOFs) for the shoulder joint and a passive slip interface (2-DOFs) for the shoulder girdle is developed in the Arizona State University [55].

Some other robotic shoulder rehabilitation orthoses powered by electromagnetic actuators are L-EXOS [56], SUEFUL-7 [57], ALE_x (commercial product developed at PERCRO lab) [58], KINARM (BKIN Technologies) [59], ETS-MARSE [60], ARAMIS [61], ARMOR [62], IKO (hybrid actuation with electric motors for shoulder) [63], mobile 3-DOFs motion assist exoskeleton [64], 5-DOFs robotic exoskeleton in SCUT lab [65], Sensoric Arm Master (SAM) [66], Shoulder Rehabilitation Robot (SRR) [67], ABLE [68] and MULOS [69].

B. Shoulder Orthoses Powered by Pneumatic Actuators

A pneumatically actuated lightweight exoskeleton, called Robotic Upper Extremity Repetitive Therapy (RUPERT), was developed for use in physical therapy by researchers at Arizona State University [70]. The latest version of this wearable 5-DOFs robotic orthosis named RUPERT IV (Fig. 4 (a)) has gone through several improvements over almost ten-year period [71]. This portable back-drivable robot is driven by unpaired compliant pneumatic artificial muscles (PAM) with a high power to weight ratio, also referred as McKibben muscles. PAM can contract or extend using the compressed air. Compared to the previous designs, RUPERT IV has added 1-DOF for shoulder joint providing shoulder external rotation and elevation [51]. Larger torques can be achieved at shoulder joint by increasing the pressure or the diameter of air muscles [72]. Composite materials are used to reduce the overall weight of this rehabilitation robot that can be worn while standing or sitting. Another important design

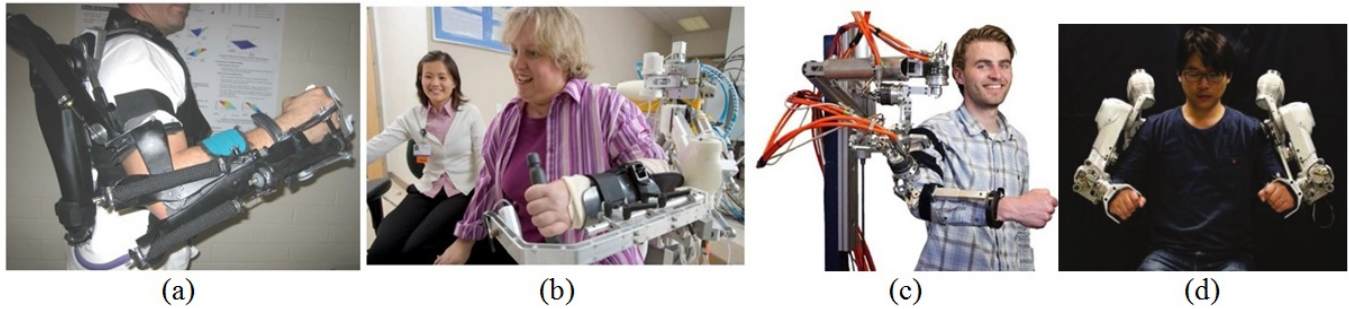


Fig. 4. (a) RUPERT IV [51], (b) Pneu-WREX [52], (c) LIMPACT [53], (d) HARMONY [54].

characteristic of this exoskeleton with adjustable lengths of arm segments is that it was developed without gravity compensation promoting practices in a natural setting [70]. However, pneumatic artificial muscles for each joint can only provide unidirectional actuation. Moreover, the restrictions at shoulder joint in this device limit the full range of motion of the human arm.

Pneu-WREX (Fig. 4(b)) developed at the University of California [73] based on passive exoskeleton T-WREX [74] is a lightweight pneumatically driven robotic orthosis for physical therapy of the upper limb. Pneu-WREX, using pneumatic actuators and a spring to balance its own weight, generates a wide range of active forces to provide naturalistic arm movements and includes a number of safety features [52]. Four out of five DOFs of this device are designed for shoulder complex [72]. Each of these DOFs is actuated by a low-friction pneumatic cylinder.

Biomimetic Orthosis for the Neurorehabilitation of Elbow and Shoulder (BONES) based on a parallel mechanism is a pneumatically actuated exoskeleton with 3-DOFs for shoulder motion [75]. A humanlike musculoskeletal shoulder robot actuated by the pneumatic artificial muscles, assembled like natural human muscles, to replicate complex shoulder movements is developed by the researchers from Osaka University [76]. Some other robotic shoulder rehabilitation orthoses powered by pneumatic actuators are SRE (using PAM) [77], “Muscle Suit” (McKibben muscles) [78], ZJUESA [79], KIST (pneumatic and electric brake actuators) [80], 7-DOFs wearable robotic arm [81] and an exoskeleton for shoulder elevation [82].

C. Robotic Shoulder Orthoses Powered by Hydraulic Actuators/Series Elastic Actuation

A compliantly actuated robotic exoskeleton LIMPACT (see Fig. 4(c)) has been developed for use in stroke therapy which consists of four rotational series elastic hydraulic motors and torsion springs [83]. The mechanical design of this robotic orthosis with 3-DOFs (actuated) at the shoulder joint is based on a passive exoskeleton called Dampace [18], the predecessor of LIMPACT, in which the Bowden cables and disk brakes were used instead of hydro-elastic actuation. The model of LIMPACT exoskeleton is divided into four sub-models with a total of 18 rigid parts combined by 20 revolute joints [53]. Both Dampace and the LIMPACT have passive self-aligning shoulder mechanisms and take into account the translational DOFs in the shoulder. Also, LIMPACT is able to align the shoulder without a controller, and a motor passively balancing

the system with gravity compensation [53]. However, such passive aligning mechanisms are confined in supporting patients during GH mobilization trainings [50]. Moreover, this robotic device currently can only be used in research facilities due to the expensive installation of its actuation system which has a large and unsafe hydraulic pump [53]. Another example of a hydraulically actuated upper limb exoskeleton with 3-DOFs for shoulder is called Sarcos Master Arm [84].

A two-armed exoskeleton called HARMONY (Fig. 4(d)) with series elastic actuators at every joint has recently been developed at the ReNeu Robotics Lab, University of Texas [54]. It provides 5-DOFs (active) for each shoulder: 3-DOFs rotations at the GH joint and 2-DOFs for the shoulder girdle movement. The developed shoulder girdle mechanism is able to change circular motions in different directions with the designed parallelogram and rotary joint. HARMONY is a stationary upper limb exoskeleton that connects to human body at three places on each side and can be adjusted to fit various body sizes. However, it could still be considered as a heavy and large robotic orthosis with complex configuration.

Another device designed for post-stroke shoulder rehabilitation with series elastic actuation is a wearable cable-driven compliant shoulder brace [85]. It is a deformable and lightweight elastic device with two Bowden cables used for power transmission. Encoders and IMU (Inertial Measurement Unit) sensors are used to measure cable lengths and orientation offsets in real time, respectively. However, this soft orthosis has a very limited mobility with just 1-DOF for shoulder abduction-adduction movement. Some other robotic shoulder rehabilitation orthoses with series elastic actuation or elastic elements found in the literature are intrinsically compliant continuum shoulder exoskeleton [86], wearable shoulder exoskeleton [87] and MUNDUS [88].

Summary: Some of the above reviewed robotic shoulder orthoses consider translational motions of shoulder girdle by translating one (ARMin II-III) or two (3-DOFs compatible exoskeleton [48]) axes of shoulder joint with coupling mechanism or by designing a special mechanical linkage [64]. The shoulder girdle movements can also be assisted using one (MGA, Pneu-WREX, exoskeleton in [89]) or more (MEDARM, NTUH-ARM, HARMONY, musculoskeletal shoulder [76]) additional active DOFs, passive self-alignment (Limpact, SUEFUL-7) or with the use of both active and passive DOFs (IntelliArm, IKO, ASSISTON-SE). It may be argued that the costs, weight and control complexity of such mechanical advancements are not worth the benefits obtained with them during the physical therapy [90]. For example, in

exoskeletons such as CADEN-7, L-EXOS and CAREX, these translational shoulder movements are compensated by body movements with fixed CGH.

Apart from the consideration of shoulder girdle movement, some other advantages of the main existing robotic shoulder orthoses are reduced weight (CAREX, RUPERT IV), availability for both arms (ARMin III, EXO-UL7, IntelliArm, HARMONY) and gravity compensation (e.g. Pneu-WREX, LIMPACT, L-EXOS, MGA). Singular positions (singularities) that can occur in the mechanisms during the movement of robotic structures is another important consideration taken into account in CADEN-7, L-EXOS, MGA and exoskeleton in [89] (by tilting the position of the motors), BONES (by restricting the workspace), NTUH-ARM (by adding extra DOF) and MEDARM (designed so that singularities occur further from the normal workspace). In mechanisms with a passive self-alignment, singularities can occur within the workspace [89]. The majority of the existing shoulder rehabilitation devices have been actuated with conventional bulky motors due to the ease of their control, availability and low cost. Cables and pulleys are used for power transmission to locate the heavy motors away from a human body. On the other hand, lightweight PAMs have a higher power to weight and power to volume ratios but are more difficult to control due to the structured nonlinearities in their dynamic model. The hydraulic actuators have even a higher power to weight ratio than PAMs but their installation in most cases is problematic and raises health and safety problems due to the nature of liquids used. To replicate the natural movements of human arm, compliant actuators with series elastic elements and other deformable actuators can also be used. Moreover, the combined types of actuation with improved functional capabilities and back-drivable transmissions can be developed to deliver more efficient and comfortable use of robotic shoulder orthoses.

IV. CONTROL STRATEGIES

Control strategies for the robotic upper limb rehabilitation orthoses are developed to repetitively guide the patients' limbs on anatomically and ergonomically feasible trajectories so that the patients can regain muscular strength. Development of these control strategies has also been an important area of research in the robot upper limb rehabilitation [47, 65, 91-96].

The control strategies for upper-limb rehabilitation robots can be classified in different ways. In one of the recent reviews on upper-limb exoskeletons, the authors categorized control methods based on input information (human biological signal, non-biological signal, platform independent method), output of the controller and controller architecture [10]. In [12], the authors considered "high-level" (assistive control, challenge-based control, haptic stimulation and non-contacting coaching) and "low-level" (impedance control and admittance control) control algorithms used by robotic devices in upper-limb rehabilitation, following the terminology proposed in [91]. In short, the former control strategies are directly intended to raise motor unit plasticity while the later regulate parameters such as impedance, admittance, force and position [12]. In [95], the exoskeleton control systems were classified based on the model (dynamic and muscle), the hierarchy (task,

high and low levels), the physical parameters (position, torque/force and force interaction) and the usage (virtual reality, teleoperation and gait). Moreover, the exoskeletons can also be controlled in different modes: active assisted, active unassisted, passive and resistive [97]. Another alternative classification (defined in [98] based on [96]) of control strategies for robot-aided rehabilitation includes three modes: assistance (passive, triggered passive and partially assistive control), correction (tunneling and coordination control) and resistance.

Most of the controllers for existing upper limb exoskeletons are assistive, which means the controller helps the patients to move their disabled arm to accomplish desired movements imitating therapist's rehabilitation assistance [91]. Different control techniques are used in recent robotic orthoses for shoulder rehabilitation to implement this concept.

Assist-as-Needed (AAN) control is an active assisting training paradigm in recent rehabilitation practices supporting patient's motion with the minimal amount of assistance. The concept behind the development of AAN algorithms is to modify the robotic assistance according to the disability level and effort put by the patients during the rehabilitation process. If the patients show some progress and recovery by incorporating their muscular strength, the robotic assistance is reduced and vice versa. This control strategy, in which robotic device does not need to operate for the full duration of the motion, increases the patient's muscle activity being one of the promising control technique in recovery. Commonly, such control algorithms incorporate the desired trajectory with a resistance field that estimates the required supportive action. Therefore, impedance schemes and adaptive controllers are usually applied within AAN control paradigm [99]. A number of AAN control strategies has been developed and implemented for shoulder rehabilitation robots as follows.

Adaptive "assist-as-needed" and force field control methods have been used for CAREX orthosis to control the cable tension [38]. An "assistance-as-needed" controller that can be adapted during the action was developed for Pneu-WREX exoskeleton with non-linear force controller for pneumatic actuators [52]. An active assisted mode has also been realized in LIMPACT orthosis. Its overall control architecture consists of a torque and an impedance controller. The inner-loop torque controller includes a Smith predictor with a lead-lag filter and the outer-loop impedance controller incorporates a gravitation vector with a state feedback controller [53]. An assistive control system has been developed for NTUH-ARM exoskeleton based on the human arm dynamics obtained with a pair of 6-axis force/torque sensors and gravity compensation [47]. To ensure the efficacy of the proposed control strategy, the authors made the Lyapunov stability analysis prior to its experimental evaluation [47].

Most of the shoulder robots (L-EXOS, MGA, SRE to name a few) use impedance or/and admittance control schemes with joint angles and torques as control inputs to govern robotic assistance. All axes in ARMin III can be controlled with an impedance scheme in addition to computed torque (CT) control and proportional derivative (PD) control [34]. The EXO-UL7 exoskeleton system has been controlled with a linear proportional-integral-derivative (PID) controller and a PID admittance controller [100]. The control scheme that

takes into account shoulder's scapulohumeral rhythm with coupling torque based on impedance has been developed for HARMONY exoskeleton [54]. The impedance control with ongoing feedback and a band-pass filter has been implemented in Shoulder Rehabilitation Robot (SRR) [67]. The safety-improved nonlinear adaptive controller has been implemented in 5-DOFs upper-limb rehabilitation exoskeleton [92]. In [101], the trajectory control strategy has been presented based on human arm movements. A Lyapunov-based control strategy implemented on the shoulder robot design is presented in [102].

For RUPERT IV, a closed-loop adaptive controller has been designed for passive task training with each DOF controlled by a PID feedback controller [51]. In addition, the shoulder controller also has an Iterative Learning Controller (ILC) which can learn from the preceding estimation on individual basis and update a suitable feedforward command. A total of 13 fuzzy rules were selected to deal with the nonlinearities caused by pneumatic actuation in RUPERT IV [51]. The detailed description of implemented adaptive active-assist and cooperative modes using the controllers in RUPERT IV is given in [103].

The impedance (IMP) or admittance (ADM) control methods are usually developed without considerations of user's intention or physical condition which might be done by implementing control systems based on the electromyographic (EMG) signals [95]. The impedance control based on surface electromyographic (sEMG) signals has been implemented in shoulder robots such as ETS-MARSE [104], SUEFUL-7 [57], motion assist exoskeletons robots [64], MUNDUS [88], musculoskeletal robot arm [76] and 5-DOFs exoskeleton in SCUT lab [65].

The control algorithms used influence the performance characteristics and efficiency of the robotic shoulder rehabilitation devices. Robust and non-linear control algorithms must be developed and implemented for the new generation of robotic shoulder rehabilitation orthoses powered by intrinsically compliant actuators. With the technological developments in the brain machine interfaces, new control systems able to identify subject's intention should be considered. Advanced AAN training strategies need to be developed and the already existing AAN strategies should be clinically evaluated to provide benchmarks in the level of assistance provided to neurologically impaired patients. There are also different ways how the developed robotic shoulder orthoses could be controlled: with the mind, control panel, joystick or other interfaces.

V. EXPERIMENTAL EVALUATIONS

Substantial work has been done in order to advance the mechanism design and some control aspects of robotic shoulder rehabilitation orthoses. However, a few attempts have been made to test the actual performance of these orthoses in clinical settings. Nevertheless, during the last decade, the robotic shoulder exoskeletons are gradually moving from research facilities to rehabilitation settings in order to provide physical therapy to patients with stroke-induced impairments, spinal cord injuries (SCI), multiple sclerosis (MS) and cerebral palsy.

ARMin II and ARMin III have been experimentally evaluated and used in clinics more than any other robotic shoulder rehabilitation orthoses. Four chronic stroke patients (in this case more than 12 months post stroke) participated in 3-4 one hour sessions per week for 8 weeks in robot-aided therapy with ARMin II exoskeleton [105]. The main measure of treatment results was Fugl-Meyer Score of the upper extremity Assessment (FMA-UE), whereas changes in evaluations such as Wolf Motor Function Test (WMFT), Catherine Bergego Scale (CBS), Maximal Voluntary Torques (MVTs) and some questionnaire were secondary outcome measures. The experimental data showed significant positive progress of arm motor function in three out of four enrolled subjects. This formed the ground for future robot-assisted clinical studies.

A large parallel-group randomised trial was conducted in four clinical centres in Switzerland with chronic stroke patients (more than 6 months) to compare the effects of conventional therapy in neurorehabilitation and the training with robotic exoskeleton (ARMin III) [106]. After the initial surveying, eligibility assessment, randomisation and exclusions, 35 subjects were assigned to conventional and 38 to robot-assisted therapies. Both groups received 45 minutes training sessions 3 times per week for duration of 8 weeks. The primary evaluation tool (FMA-UE) was tested at different periods of the clinical trial. The findings showed that subjects who received robot-aided therapy had much greater advancements in affected arm's motor function consequently leading to a conclusion that exercises with a robotic orthosis can more effectively increase the motor function in stroke patients than traditional manual physical therapy. Another recent clinical study with ArmeoPower exoskeleton involved 35 stroke patients with hemiplegia who received 40 one hour sessions 5 times a week for 8 weeks and were assessed on FMA and Modified Ashworth (MA) scales [107]. The outcomes of this trial also indicated that use of the robotic exoskeleton can enhance motor function in upper limb rehabilitation.

Twenty chronic stroke subjects used BONES exoskeleton receiving single joint and multi-joint therapies 3 times per week for a duration of 4 weeks [108]. Box and Block Test (BBT) was the main assessment measure, while secondary outcome variables were FMA, WMFT, Motor Activity Log (MAL) and some tests on shoulder strength and speed. The findings suggest that use of a robotic device increased the motor function of patients but no major differences were reported in the outcome of multi-joint and single-joint trainings. The AAN control strategy developed in [52] has been employed in this study.

L-EXOS orthosis was evaluated with 9 chronic stroke subjects for 6 weeks. Clinical study with kinesiology assessment based on EMG analysis has been conducted and evaluation measures such as FMA and MA has been performed [109]. As a result, the statistical improvements of measured variables (shoulder motion parameters) with some correlations are reported. The favorable results were attained with the NTUH-ARM exoskeleton in clinical trials with six stroke patients verifying the effectiveness of the AAN control [47]. Fourteen stroke subjects with hemispheric lesions were enrolled in clinical study with 6-DOFs dual exoskeleton robot

Table I. Summary Table of Existing Robotic Shoulder Rehabilitation Orthoses

Device (based on)	UL segment	DOF Total/Shoulder	SG motion	Type	Control method	Advantages	Disadvantages	Clinical Study (sp)
ARMin III* <i>ArmeoPower</i>	S+E+(W)	6a/3a	E/D - c	e	IMP, PD, CT	Back-drivable, available for both arms, no extra actuators for SG aligning	High inertia, simple model of (limited) shoulder motion	yes
EXO-UL7 (<i>CADEN-7</i>)*	S+E+W	7a/3a	no	e/c-d	PID, ADM, EMG	Low inertia, negligible backlash, high stiffness links, mechanical stops, emergency switches and driven pulleys, available for both arms, KS considered	Constrained in the transportability and adjustability, motors are heavy and big	yes
IntelliArm*	S+E+W	7a/(4a + 2p)	E/D - 1a, P/R - 2p	e/c-d	VR	Self-alignment (no additional adjustment required), accurate SG motion, available for both arms	Motors are heavy, no actuation for P/R, singularities occur	no
CAREX*	S+E	5a/3a	no	e/c-d	IMP, AAN	Lightweight, push/pull forces without rigid links and joints, actuators remotely located	Stationary, no shoulder girdle control	no
RUPERT IV*	S+E+W	5a/2a	no	PAM	FFC, PID	Lightweight, easily wearable, back-drivable	Limited shoulder movements, slow motion only	yes
Pneu-WREX* (<i>T-WREX</i>)	S+E	5a/4a	P/R - 1a	p	IMP, PD, AAN	Gravity compensated, control safety systems, visual and audio feedback	Only slow limited movements	yes
LIMPACT * (<i>Dampace</i>)	S+E	4a/(3a + 2p)	passive	rHEAs	IMP	Self-alignment, gravity compensated	Expensive installation of its actuation system, singularities occur	no
L-EXOS*	S+E+W	5a/3a	no	e/c-d	SMC, IMP PD	Gravity compensation, low impedance, high payload, actuators remotely located, improved stiffness	Heavy, expensive to manufacture and maintain	yes
BONES *	S+E+W	6a/3a	no	p	AAN	Parallel structure, allows forearm rotation without the use of a ring bearing, allows use of large actuators (need not to be moved), KS considered	Reduced workspace, no SG control	yes
NTUH-ARM *	S+E	7a/6a	E/D - 1a, P/R - 1a	e	AAN, IMP, EMG	Adjustable to various lengths of arm, no circular guide for shoulder motion, full SG control, two 6-DOF force/torque sensors, safety issues, KS considered	Heavy, redundant design	yes
<u>MEDARM</u>	S+E	6a/5a	E/D - 1a, P/R - 1a	e/c-d	-	Independent monitoring and control of all 5-DOFs of the shoulder complex	Complex structure, circular approximation of CGH motion (misalignment occurs), no real prototype (only Planar 3DOF)	no
IKO*	S+E+(W)	5a/(3a + 3p)	passive	hybrid	PI	Self-alignment	Singularities occur	no
<u>MGA</u>	S+E+(W)	5a/4a	E/D - 1a	e	IMP, ADM, PD	Gravity compensation, allows high humerus elevation (147°)	Additional motor, high inertia, not back-drivable, no actuation for P/R (misalignment occurs)	no
ASSISTON-SE	S+E	6a/(5a + 1p)	E/D - 1a, P/R - 1a	e/SEA	-	Back-driveable, both passive (slider) and active shoulder girdle control	Mechanism dimensions and transmission ratios are not optimized, proposed actuation is not implemented	no

UL – upper limb; S – shoulder; E – elbow; W – wrist; E/D - elevation/depression; P/R - protraction/retraction; SG – shoulder girdle; PAM - pneumatic artificial muscles; rHEAs - rotational hydro-elastic actuators; SEA – series elastic actuation; IMP – impedance, PD – proportional derivative; PID - proportional–integral–derivative; CT – computed torque; ADM – admittance; VR – virtual reality based; FFC – feed forward control; EMG – electromyogram based; SMC – sliding mode control; c – coupling; a – active; p – passive; e – electric; c-d – cable-driven, p – pneumatic; KS – kinematic singularities; sp – stroke patient.

*Journal Publication, Highly cited Conference Paper (>80)

Table II. Shoulder exoskeletons used in clinical studies

Device	Shoulder DOF	Control method	Patient #	Clinical Outcome
ARMin III	3 active	IMP, PD, CT	38 cs	↑FMA
ArmeoPower	3 active	IMP, PD, CT	35 s	↑FMA ↑MA
Pneu-WREX	4 active	IMP, PD, AAN	23 cs	↑FMA ↑BBT
BONES	3 active	AAN	20 cs	↑BBT ↑FMA
EXO-UL7	3 active	PID, ADM, EMG	10 s	↑ROM
L-EXOS	3 active	IMP, PD	9 cs	↑FMA ↑MA
NTUH-ARM	6 active	AAN	6 s	↑FMA

c(s) – chronic (stroke); ROM – ranges of motion, # - number

ARAMIS in 50 minute sessions 5 times a week for a duration of 7 weeks [110]. The FMA scores significantly increased for all patients at the end of training process.

RUPERT IV exoskeleton has been tested in two feasibility studies using reaching-out tasks in a 3D virtual reality environment to validate the effectiveness of a task based robot-assisted repetitive therapy [111]. Six stroke patients were involved in the first study to receive 4 weeks (one-hour session 3 times per week) clinic based robot-assisted therapy and two other patients used this wearable device for the same period on a daily basis at home. The clinical results showed that only few of the involved patients demonstrated improvements and statistical evaluations have shown that only half of the patients trained in clinic had some functional improvement. Both subjects who used RUPERT IV in a home setting showed significant advancements in their performance. However, there is inconsistency in the given results and mainly it is because of the small number of patients involved with a significant variance between their disability levels. Moreover, the duration of these studies might be not long enough to achieve a proper conclusion [111].

There are also other chronic/stroke patient (c/sp) interaction studies reported in the literature with robotic shoulder rehabilitation orthoses such as Pneu-WREX (23 csp) [112], ARMOR (8 sp) [62], ABLE (7 sp) [113], EXO-UL7 (10sp) [114], IntelliArm (3 sp) [45] and MUNDUS (3 SCI and 2 MS) [88].

CAREX has been tested with healthy subjects and one stroke patient. However, more experiments are still needed in order to test larger ranges of GH joint motions [38]. Experimental evaluations with the HARMONY exoskeleton have demonstrated that the controller produced correct movement for scapulohumeral rhythm and also induced gentle forces when the shoulder exhibited an abnormal rhythmic motion. Some of the other experimental evaluations with healthy subjects (hs) were performed with the following shoulder robotic orthoses: ALEx (6-hs) [58], "Muscle Suit" (5-hs) [78], SUEFUL-7 (2-hs) [57], motion assist robot (2-hs) [64], CADEN-7 (1-hs) [37] and MULOS (1-hs) [69].

Several clinical trials with stroke patients have been conducted using different shoulder exoskeletons. The recent findings of such evaluations have showed some motor function improvements in subjects' upper limb. Moreover, modern technologies like human-robot interfaces with a virtual reality environment, different games and functional exercises boost the intensity of training process, increasing the efficiency of such robotic devices in upper limb rehabilitation. However, more studies with various shoulder exoskeletons are needed involving larger groups of patients with different levels of neurological impairments to confirm their effective physical therapy outcomes. Furthermore, only a few of the existing robotic shoulder orthoses can be tested at home based settings. Table II shows the clinical outcomes of various selected studies with the developed shoulder robotic orthoses, their number of DOFs for shoulder and implemented control strategies. Even though the same assessment measures are mostly used in these trials, the direct comparison is difficult due to differences in patients' disability levels, age and initial evaluation scores, duration of the therapies, study protocols and types of training sessions.

VI. DISCUSSION AND FUTURE DIRECTIONS

During the last two decades, a large number of robotic shoulder rehabilitation orthoses have been developed to assist people with upper-limb disability and extensive research efforts have been dedicated to advancing the mechanical design and control strategies for such robotic orthoses. This work provides an up to date review of literature with a focus on mechanism design and control for robotic shoulder rehabilitation orthoses. It will be useful to analyze, evaluate and integrate improvements in mechanical mechanisms and control systems of existing devices when designing future shoulder exoskeletons. This will aid in developing a standardized rehabilitation framework for the robot assisted shoulder physical therapy.

The main challenges are that these exoskeletons should be accurately aligned with the human joints, safely adjusted to match different individuals' size and provide naturalistic complex shoulder movements. The robotic shoulder rehabilitation orthoses that take into consideration only three rotational shoulder DOFs provide less workspace for patients and cause discomfort during the training sessions. Hence, to avoid the misalignments between the exoskeleton and human joints and provide larger ranges of motion, shoulder girdle mechanisms should be designed and implemented.

In contrast to designing a mechanism aligned with the human joints, it might be better to consider building an exoskeleton with parallel structure with the same workspace and ranges of motion as the human shoulder [115]. Some shoulder mechanisms with parallel structures are considered in [41, 50, 55, 75, 116, 117]. In fact, robotic devices with parallel structures can be more compact, stiffer, having less inertia and higher load carrying capacity compared to the serial mechanisms [118]. Time spent on the adjustment procedures can also be saved with such parallel shoulder orthoses. However, the drawback of these parallel structures is reduced workspace and mechanical interference between links.

The design of the robotic exoskeletons could be enhanced by using biomechanical principles of human motion [119, 120]. Thus, it is important for robotic specialists to thoroughly study shoulder biomechanics and cooperate with physiologists when designing future robotic orthoses. Understanding the shoulder anatomy and movement characteristics, structure of the bones and articulations, muscle functions and their points of attachments will give a greater perspective towards the development of future robotic rehabilitation orthoses that can stimulate the natural movements of the shoulder complex. New designs of robotic shoulder orthoses should not only reproduce the anatomical structure of shoulder but also integrate its biomechanics, considering the forces and torques at the shoulder complex during the motion of the arm. Hence, it is worth addressing the following questions regarding the physiology of the human shoulder:

- What muscles are involved in common shoulder movements during rehabilitation training?
- What are the forces in these muscles (biarticular muscles) and joint reactions during shoulder movements?
- What neural mechanisms are involved during shoulder rehabilitation therapy?

- What are the metabolic energy expenditures of the patient with the robotic shoulder orthosis assistance?

In fact, no existing technological components of an actuated machine can outperform the functionality of the human muscles yet. So, the selection of the type of actuation plays one of the major roles in the mechanism design for shoulder robotic rehabilitation orthoses. Electromagnetic actuators, PAM, hydraulic and series elastic actuators have their own inherent advantages and disadvantages. There is always a trade-off between the exoskeleton's functional capacity and weight. After all, the intrinsic elasticity of lightweight PAMs providing compliant actuation makes them a promising technology in the field of rehabilitation robotics actuation.

As all people are different in size and have unique individual body characteristics, adjustable elements and simpler mounting methods are needed. New developments in soft robotics can make the future exoskeletons more flexible so that the structure of the robot will bend with the body and it will be simpler in fitting. Most of the current shoulder orthoses look unappealing to a general public but with the lighter "exo-suits" they could be worn underneath the cloth. To overcome the problem caused by the forces added to the body by such soft suits, the future designs should be able to change their frames from solid to soft when needed. The exoskeletons made completely of texture with inflatable parts can be utilized to exchange off material weight and structure. 3D printers using materials with variable mechanical properties can also be used to construct the devices after scanning certain parts of the individual's upper body.

Reducing the cost of the developed shoulder robotic exoskeletons is another important challenge that needs to be overcome by the developers. Current commercial upper limb rehabilitation robots are highly expensive (e.g. ArmeoPower cost 250k EUR [15]). Moreover, their cost does not include the maintenance and physical therapy sessions. The more the already developed commercial products enter the market, conduct clinical studies and increase their sales, the lower will be their final cost. Perhaps, focusing only on a shoulder complex with the optimized robotic orthosis design can bring the cost of the new devices down. Small compact air compressors with replaceable cartridges within the inflatable exoskeletons can also drastically reduce the cost of these upper limb robots. Currently, research teams like Otherlab, San Francisco, rely on high-strength fabric and air power to develop the low cost and lightweight exoskeletons [121]. Better networking between research laboratories and business people, connections to medical and insurance companies, proper regulations and social security are needed to increase the cost-effectiveness of such robotic assistive devices. Finally, rehabilitation robots are not meant to replace the human job but rather to be an effective subset of this job. As the cost of personnel will be rising while the cost of technology will go down, the shoulder robotic exoskeletons will continue to become safer, more reliable and practical.

There is no single recipe for constructing ideal shoulder robotic orthosis. The future shoulder exoskeletons should be

safe, compliant, lightweight, adjustable, low-cost and easy to use with user friendly interfaces. Such robotic rehabilitation devices with embedded force and motion sensors will provide more efficient physical therapies to patients with shoulder impairments. A completely wearable, intrinsically compliant shoulder orthoses will be another desirable feature. New control algorithms, advanced electronics, software and machine learning tools will constitute the core of the future research platforms. Research findings in the fields of lower limb rehabilitation, biomechanical modeling, neurophysiology, control systems, mechanism synthesis, and additive manufacturing should also be incorporated in the development of intelligent robotic orthoses for shoulder rehabilitation. To sum up, the further research in robotic shoulder exoskeletons should consider:

- optimum mechanism design for shoulder girdle's main DOFs
- matching the robot's workspace to the entire workspace of the human shoulder taking into account translations of GH joint
- developing an accurate musculoskeletal, kinematic and dynamic models of the human shoulder taking into account all DOFs and ROM of the shoulder complex
- acquiring more experimental/clinical data on the human physiological reaction to mechanical shoulder exoskeleton use
- modelling compliant actuation, designing soft adjustable structures, actuator-brake coupling for gravity compensations, etc.
- employing latest advances in energy harvesting systems: high pressure compressors, fuel cells, flexible batteries, etc.
- developing new faster control algorithms with real time force-feedback controllers in actuation and AAN training strategies.
- collaboration and networking with the researchers from related different fields of study, physiotherapists and industry partners.

Despite the rapid progress in robotic upper limb rehabilitation devices during the last decade, still much remains to be done and we look forward to the innovative contributions that will come about in this exciting area of research.

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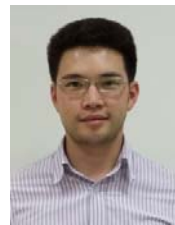
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