International Journal of Intelligent Robotics and Applications (2018) 2:283–295
https://doi.org/10.1007/s41315-018-0064-8

REGULAR PAPER

Upper limb rehabilitation using robotic exoskeleton systems: a systematic review

Naqash Rehmat[1] · **Jie Zuo**[2] · **Wei Meng**[2,3] · **Quan Liu**[2] · **Sheng Q. Xie**[3] · **Hui Liang**[4]

Received: 24 May 2018 / Accepted: 9 August 2018 / Published online: 17 August 2018

Abstract

Exoskeleton assisted therapy has been reported as a significant reduction in impairment and gain in functional abilities of stroke patients. In this paper, we conduct a systematic review on the upper limb rehabilitation using robotic exoskeleton systems. This review is based on typical mechanical structures and control strategies for exoskeletons in clinical rehabilitation conditions. A variety of upper limb exoskeletons are classified and reviewed according to their rehabilitation joints. Special attentions are paid to the performance control strategies and mechanism designs in clinical trials and to promote the adaptability to different patients and conditions. Finally, we analyze and highlight the current research gaps and the future directions in this field. We intend to offer informative resources and reliable guidance for relevant researcher's further studies, and exert a far-reaching influence on the development of advanced upper limb exoskeleton robotic systems.

Keywords Robot-assisted rehabilitation · Upper limb exoskeleton · Clinical trials

1 Introduction

Stroke is one of the major health care issues in the United States (Go et al. 2016), Japan (Tsugawa et al. 2013), UK (Townsend et al. 2012), European Union (Nichols et al. 2012), Australia, New Zealand (Stroke Foundation of New-Zealand), and rest of the world (Lopez et al. 2006). In the United States, it is the second biggest cause of death and major cause of adult disability (Stroke Foundation of New-Zealand). According to figures from the stroke foundation of New Zealand, annually around 0.795 million people suffer from stroke and 76.72% of them are new strokes (http://www.cdc.gov/dhdsp/data_statistics/fact_sheets/fs_stroke/). The stroke data from the less developed or developing countries are not regularly updated and, therefore not easily available. However, it is estimated that percentage of stroke-related disability is a lot higher in these countries (Lopez et al. 2006; Bertani et al. 2017). A stroke occurs when brain cells are impaired due to interruption of blood supply to the brain or due to accumulation and subsequent compression of the brain due to rupturing of blood vessels. As a result, the stroke patient experiences a loss of physical strength on one side of the body, paralysis or hemiplegia. This greatly affects the patient's ability to perform daily life work and activities. After the stroke, patients are advised to undergo therapy sessions to reduce impairment and recover functional ability. In the last two decades, various robotic systems have been developed to assist stroke survivors during the rehabilitation phase. These devices can assist patients during rehabilitation phase to restore some function lost due to this injury. Two kinds of robotic devices are currently available for upper limb rehabilitation, including an effector robots and exoskeleton robots. An end effector robot is based on industrial robot arm; where human upper limb (hand or forearm) is attached to the robot through one point and the robot exert force only at this point (Frisoli et al. 2007). With one physical interface, it is very difficult to fully determine the posture of the upper limb. This is due to the fact that upper limb consists of two unconstrained parts (humerus and forearm) and they are free to move about their pivot at shoulder and elbow. With only one physical interface

---

✉ Sheng Q. Xie
s.q.xie@leeds.ac.uk

[1] Department of Mechanical Engineering, The University of Auckland, Auckland, New Zealand

[2] School of Information Engineering, Wuhan University of Technology, Wuhan, China

[3] School of Electronic and Electrical Engineering, University of Leeds, Leeds, UK

[4] College of Electromechanical Engineering, Qingdao University of Science and Technology, Qingdao, China

an end-effector robot cannot control each individual joint independently. As a result, an end-effector robot has a limited workspace with movement in either robot joint space or Cartesian space. Examples of end-effector devices are MIT-Manus (Krebs et al. 2004), MIME (Lum et al. 2005), ARM Guide (Reinkensmeyer et al. 2000), Bi-Manu-Track (Formaggio et al. 2015) and Gentle/s system (Coote et al. 2008). An exoskeleton type device has a similar structure to the human arm and is attached to the side of the human arm at multiple locations. The joints axis of exoskeleton robot matches that of the human upper limb joint axis. The physical interface at multiple locations makes it much easier to fully determine posture during the movement. This also allows controlling the torque applied to each individual joint. Since the exoskeleton is attached to the side of the human arm, therefore, it can cover the whole range of upper limb motion. With exoskeleton robot, any part of upper limb can be targeted for training. Unlike an end effector robot, an exoskeleton robot has a large range of motion. Examples of upper limb exoskeleton devices are SUEFUL7 (Gopura et al. 2009), ARMin III (Nef et al. 2015), CADEN (Perry et al. 2007), RUPERT (Huang et al. 2016). The robotic systems used for upper limb rehabilitation can be studied based on their mechanical structure, control system, and clinical applications. The mechanical configuration (Bertani et al. 2017; Lo and Xie 2012; Young and Ferris 2017; Veale and Xie 2016; Bulboacă et al. 2017; Lee and Guo 2010; Furukawa et al. 2017; Niyetkaliyev et al. 2017; Borzelli et al. 2017; Huysamen et al. 2018) and control systems (Anam and Al-Jumaily 2012; Meng et al. 2015; Calanca et al. 2016; Bundy et al. 2017; Mushage et al. 2017; Wu et al. 2018; Li et al. 2017; Treadway et al. 2018; Madani et al. 2017) have been reviewed previously. A detailed insight on various end effector based system and their application in stroke rehabilitation have also been carried out (Poli et al. 2013). Gopura et al. (2016) produced a detailed study on the effectiveness of the robotic system in upper limb rehabilitation, however only few exoskeleton based studies were discussed in that review. Chang and Kim (2013) reviewed various end effector and exoskeleton based clinical studies. But this review discussed only four studies using the exoskeleton to provide rehabilitation. So in this paper, we will review various studies on upper limb rehabilitation using the exoskeleton based system.

To the authors' best knowledge, there has not been a comprehensive review on design and control of upper limb rehabilitation exoskeleton in clinic trails. Hence we intend to conduct an systematic and informative survey, which can be served as a reliable guidance for scientists and engineers when they engage in soft rehabilitation robots. In particular, the all-round comparisons of existing rehabilitation robots are based on the published available data, to make researchers fully aware of the limitations and advantages of diverse mechanical designs and control schemes. From the research point of view, this paper will also generate the current research gaps and future directions, promoting the advent of more compliant, adaptable, intelligent and mature robots to satisfy the sharply increasing rehabilitation demands. The rest of paper is organized as follows. Sections 2 and 3 clarifies upper limb exoskeletons with various mechanical structures and their control strategies. In Sect. 4, clinical trial performance of these exoskeletons are introduced and compared. Section 5 discusses and analyses the research limitations and future directions. Finally, conclusions are drawn in Sect. 6.

2 Mechanical design

The human upper limb is a complex area with three different movement complex; shoulder complex, elbow complex, and wrist joint complex (Al-Fahaam et al. 2016; Oguntosin et al. 2017). With these three-movement complexes, the upper limb has total 9 degrees of freedom (Gopura and Kiguchi 2009). The shoulder joint effectively has 5 degrees of freedom, 3 degrees due to Glenohumeral joint and 2 degrees due to sternoclavicular joint (Gopura and Kiguchi 2009). The movement at the shoulder joint is shoulder abduction/adduction, shoulder flexion/extension, internal/external rotation, shoulder depression/elevation and retraction/protraction. The elbow and wrist joints each have 2 degrees of freedom i–e elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and wrist ulnar/radial deviation. Majority of the exoskeleton robots developed for upper limb provide actuation at only shoulder and elbow (Nef et al. 2015; Niyetkaliyev et al. 2017; Li et al. 2017; Frisoli et al. 2012a, b; Keemink et al. 2018; Ullauri et al. 2015; Reinkensmeyer et al. 2012; Colomer et al. 2013a; Milot et al. 2013; Loureiro et al. 2014; Klamroth-Marganska et al. 2014). Only a few devices provide additional actuation for the forearm, wrist and sternoclavicular joints (Ball et al. 2007). Only one exoskeleton [UL-EXO7 (Kim et al. 2013; Byl et al. 2013)] out of ten used in clinical trials support 7 degrees of freedom, the remaining only provides assistance at the shoulder (3DOF) and elbow joint (1DOF) (Frisoli et al. 2008, 2012a, b; Reinkensmeyer et al. 2012; Colomer et al. 2013a; Milot et al. 2013; Loureiro et al. 2014; Klamroth-Marganska et al. 2014; Kim et al. 2013; Housman et al. 2007, 2009; Fazekas et al. 2007; Iwamuro et al. 2008; Nef et al. 2009; Staubli et al. 2009; Byl et al. 2013). By training shoulder and elbow joint they cover the entire range of movement for upper arm. However their effectiveness in promoting the use of an entire upper limb is limited as most of the daily life task involves using hand and wrist in lifting, eating, drinking and moving the objects etc. To successful retrain stroke survivors in activities of daily living assisted movement should also be delivered to lower arm and hand. Whilst designing the mechanical structure of exoskeleton the mechanism for the centre of rotation of shoulder joint must also be considered. A lot of devices assume shoulder movement by only considering the movement of the Glenohumeral joint as “ball and socket type joint”. This is a not correct assumption as the centre of rotation of human shoulder changes with the movement of shoulder joint (Lee and Guo 2010; Gopura and Kiguchi 2009). This can cause misalignment between the robot shoulder joint and human shoulder joint. This misalignment can cause pain in the shoulder joint and can have bad effects on patient recovery. The effect of this misalignment must be considered during the design process and appropriate design changes should be made to compensate this. Likewise, to achieve multi-DOF motion for wrist or ankle joint, researchers proposed parallel actuating configuration (Li et al. 2017, 2018; Jamwal et al. 2016; Wan et al. 2016; Andrikopoulos et al. 2015a, b). However, these parallel-type exoskeletons seem to be mainly designed for ankle rehabilitation, since the redundant structure are not accepted in upper limb rehabilitation.

Exoskeleton reviewed in this paper can be categorized into three types: actuated by a motor, actuated by pneumatic muscle and non-motorised actuation (such as hydraulic or spring). L-Exos (Frisoli et al. 2008, 2012a, b), UL-Exo7 (Kim et al. 2013; Byl et al. 2013), GENTLE/G (Loureiro et al. 2014), REHAROB (Fazekas et al. 2007) and ARMin (Li et al. 2017; Milot et al. 2013; Nef et al. 2009; Staubli et al. 2009) are actuated using motors (Fig. 1). Pneu-Wrex (Reinkensmeyer et al. 2012) and BONES (Milot et al. 2013) are based on pneumatic muscles, as shown in Fig. 1f. T-Wrex and its commercial version ARMEO Spring only provides gravity support to the whole arm with no robotic actuation (Colomer et al. 2013b; Iwamuro et al. 2008; Housman et al. 2007, 2009b) in Fig. 1g. Table 1 provides the detail of the studies untaken using an exoskeleton system. The clinical trials of these exoskeletons showed their effectiveness in reducing impairment due to stroke. However, there is no evidence to suggest that particular type of actuation is more help and clinically beneficial to the patients.

3 Control strategies

Several types of control strategies have been used to control the movement of upper limb exoskeleton. The exoskeleton can basically operate in three different ways: passive (robot driven), active (patient driven) and challenge (robot resists the applied force). If the robotic device is active and the patient is passive during the therapy session than it is a robot driven control strategy or passive strategy. Similarly, if the patient is active and the robot is passive than it is a patient-driven control or active strategy. In addition to these, a robot can also resist patient movement to make it more challenging for the patient. This is an example of challenge based control strategy. The requirements of these methods are different from each other. The passive mode of operation is based on trajectory control, whereas in the active and challenge modes, control decision is based on the measurement of interaction force between the human and exoskeleton. The

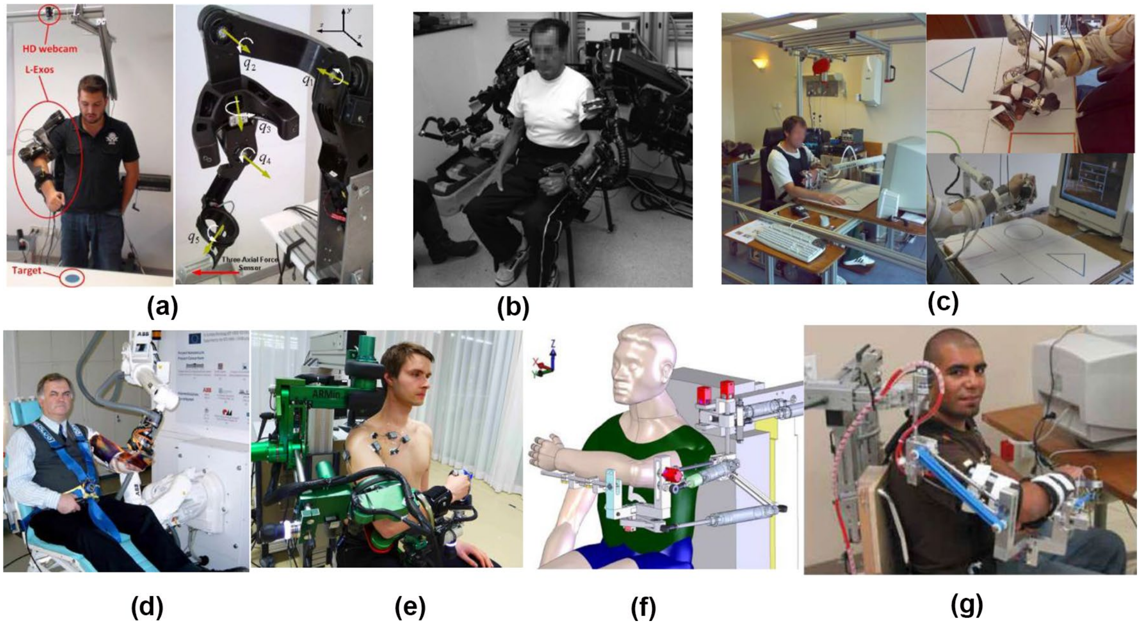

Fig. 1 Upper limb rehabilitation exoskeleton (**a**–**g**) is reprinted from Frisoli et al. (2012a), Loureiro et al. (2014), Byl et al. (2013), Fazekas et al. (2007), Staubli et al. (2009), Reinkensmeyer et al. (2012), and Housman et al. (2009b) respectively

Table 1 Exoskeletons and their control strategies

Exoskeleton	Actuated DOF	Actuators	Control strategy	In comparison to conventional therapy
T-Wrex (Housman et al. 2007, 2009a; Iwamuro et al. 2008)	5 DOF	LP	Patient-driven with gravity compensation	Effective
Active Joint Brace (Li et al. 2018; Stein et al. 2007)	1 DOF	EM	Patient-driven with EMG signals	Effective
REHAROB (Fazekas et al. 2007)	3 DOF	EM	Robot-driven	Comparable
L-Exos (Frisoli et al. 2008, 2012a, b)	5 DOF	EM	Patient-driven with impedance control	Effective
ARMin (Klamroth-Marganska et al. 2014; Nef et al. 2009; Staubli et al. 2009)	4, 5 and 6 DOF for ARMin I, II and III respectively	EM	Robot-driven with position control and patient-driven with impedance control	Effective
Pneu-Wrex (Reinkensmeyer et al. 2012)	4 DOF	PMA	Patient-driven with Assist-as-needed	Effective
ARMEO Spring (Colomer et al. 2013b)	5 DOF	LP	Patient-driven with gravity compensation	Effective
UL-EXO7 (Kim et al. 2013; Byl et al. 2013)	7 DOF	EM	Robot-driven with admittance control	Effective
BONES (Milot et al. 2013)	4 DOF	PMA	Patient-driven with AAN	Effective
Gentle/G (Loureiro et al. 2014)	3 active and 3 passive DOF	LP and EM	Robot and patient-driven with gravity compensation	Effective
T-Wrex (Housman et al. 2007, 2009a; Iwamuro et al. 2008)	5 DOF	LP	Patient-driven with gravity compensation	Effective
Active Joint Brace (Stein et al. 2007)	1 DOF	EM	Patient-driven with EMG signals	Effective

LP linear spring, *EM* electric motor, *PMA* pneumatic muscle actuators

effectiveness of active and passive control strategies have analyzed in various exoskeleton robots (Frisoli et al. 2008, 2012a, b; Reinkensmeyer et al. 2012; Colomer et al. 2013a, b; Milot et al. 2013; Loureiro et al. 2014; Klamroth-Marganska et al. 2014; Kim et al. 2013; Housman et al. 2007, 2009a; Fazekas et al. 2007; Iwamuro et al. 2008; Nef et al. 2009; Staubli et al. 2009; Byl et al. 2013), as shown in Table 1.

Patient-driven (passive) control strategy was tested in a clinical trial of REHAROB (Fazekas et al. 2007). The result showed that robot therapy in combination with conventional therapy can be beneficial, as no significant difference was observed in robot therapy group and conventional therapy group. The patient-driven control strategies have been implemented in T-Wrex (ARMEO Spring) (Colomer et al. 2013b; Housman et al. 2007, 2009a; Iwamuro et al. 2008), L-Exos (Frisoli et al. 2008, 2012a, b), ARMin (Milot et al. 2013; Nef et al. 2009; Staubli et al. 2009), UL-Exo7 (Kim et al. 2013; Byl et al. 2013), BONES (Milot et al. 2013), Pneu-Wrex (Reinkensmeyer et al. 2012), AJB (Stein et al. 2007) and Gentle/G (Loureiro et al. 2014). T-Wrex therapy system delivers rehabilitation training by providing the gravity compensation to entire arm (Housman et al. 2007, 2009a; Iwamuro et al. 2008). With no robotic actuation, the T-Wrex rehabilitation system is always patient driven. This ensures that the user always had to initiate the movement. Due to this self-initiation of the patient, the clinical results favored T-Wrex based therapy training over conventional training with statistically significant gain (Housman et al. 2007, 2009a; Iwamuro et al. 2008). This result was further verified in a clinical trial of ARMEO Spring (A commercial version of T-Wrex) (Colomer et al. 2013b). In L-Exos, the patient-driven strategy was implemented through impedance control to provide guided assistance (Frisoli et al. 2008, 2012a, b). Gravity support was also added to ensure that patient gets a sense of arm floatation in space. Clinical trials showed that significant improvement in impairment reduction can be achieved by training with L-Exos (Frisoli et al. 2008, 2012a, b). In UL-Exo7, the patient-driven strategy is implemented with an admittance control (Kim et al. 2013; Byl et al. 2013). Here gravity and friction compensation are also added into the control scheme. With patient-driven strategy, a clinical trial of UL-Exo7 compared the effects of unilateral and bilateral training on upper limb impairment. The result did not show any significant difference between bilateral and unilateral therapy training (Kim et al. 2013; Byl et al. 2013). The ARMin (Milot et al. 2013; Nef et al. 2009; Staubli et al. 2009) and Gentle/G system (Loureiro et al. 2014) can work in both robot driven and patient-driven mode. In ARMin, the robot-driven mode is based on position control and the patient-driven mode is based on impedance control. Due to both robot-driven and patient-driven mode, a patient can practice intensive and task-specific exercises. The clinical trials of ARMin (I, II and III) validated this with a significant gain in functional abilities and impairment reduction (Milot et al. 2013; Nef et al. 2009; Staubli et al. 2009). The Gentle/G provides gravity compensation using a pulley system and support 3 DOF movements through haptic master robot (Van der Linde et al. 2002). The clinical trial of Gentle/G compared conventional therapy with robot therapy by following two different training protocols. The result showed a higher gain in the robot phase of the training (Van der Linde et al. 2002). Patient-driven exoskeleton control can also be achieved from EMG based control. An EMG based control algorithm was clinically tested with an Active Joint brace (Stein et al. 2007). During the trial, EMG signals were measured from flexor and extensor muscles of elbow joint and assistance was provided based on these measurements. The trial produced comparable results to the other control strategy indicating that EMG based control strategy is as effective as the other control strategy (Frisoli et al. 2008, 2012a, b; Reinkensmeyer et al. 2012; Colomer et al. 2013a, b; Milot et al. 2013; Loureiro et al. 2014; Klamroth-Marganska et al. 2014; Kim et al. 2013; Housman et al. 2007, 2009a; Fazekas et al. 2007; Iwamuro et al. 2008; Nef et al. 2009; Staubli et al. 2009; Byl et al. 2013; Stein et al. 2007). Assist as needed (AAN) strategy was implemented in Pneu-Wrex (Reinkensmeyer et al. 2012) and BONES (Milot et al. 2013). Both devices were pneumatically actuated and cover a wide range of motion for the upper limb. A sliding adaptive control with gravity compensations was implemented in Pneu-Wrex (Reinkensmeyer et al. 2012). This assists by estimating the patient's effort by approximating the position-dependent forces required to finish the task. The control scheme used in BONES is similar to Pneu-Wrex. The Patient's ability to complete the task was estimated in real-time by using the tracking error to drive a computer model. A forgetting factor was added in both Pneu-Wrex and BONES to prevent slacking. The clinical trial of Pneu-Wrex and BONES showed positive results for assist-as-needed control strategies. Pneu-Wrex based training revealed that 3D training with AAN is better than conventional tabletop exercises. A clinical trial of BONES showed that therapy training with BONES is effective however there is no significant clinical benefit of single joint therapy over multiple joint functional training and vice versa.

While many studies have demonstrated that training with different control strategies reduces motor impairment as assessed with various outcome measures, the only significant results observed is that patient-driven control strategy with or without robotic actuation is more beneficial. This could be due to the intense effort put in by patients, resulting in impairment reduction and motor recovery. Therefore it can be said that patient-driven strategy is better than a robot driven strategy to the due inherent self-initiation property of this method. However, which control scheme with patient-driven strategy (Position control, Impedance, and Admittance, Assist-as-needed, EMG or gravity support) is more effective for a certain upper limb disability is yet to be determined and should be the topic of future clinical trials.

4 Clinic robot-assisted rehabilitation

Only seventeen papers related with exoskeleton-assisted rehabilitation have reported the clinical trial data, including 309 patients met the inclusion criteria, as shown in Table 2. Out of seventeen, eight studies were random control trials, five studies were before-after (BA) studies and remaining studies were single case trial (SCS). Some of these selected studies focused on exoskeleton assisted therapy versus conventional therapy method (Bertani et al. 2017; Bulboacă et al. 2017; Loureiro et al. 2014; Klamroth-Marganska et al. 2014; Fazekas et al. 2007; Reinkensmeyer et al. 2012; Housman et al. 2007, 2009b). Another studies looked at the effects of the individual robotic device on upper limb rehabilitation following stroke (Treadway et al. 2018; Frisoli et al. 2008, 2012a, b; Colomer et al. 2013a; Milot et al. 2013; Iwamuro et al. 2008; Nef et al. 2009; Staubli et al. 2009). Two studies compared the bilateral training method with unilateral training using exoskeleton device (Kim et al. 2013; Byl et al. 2013). One study focused on effects of EMG based exoskeleton device for upper limb rehabilitation (Stein et al. 2007). Control group performed self-range of movement including strength training, gravity support was provided. Experimental group performed three repetitions of 10 therapy games available with T-Wrex in (Housman et al. 2007; Reinkensmeyer et al. 2012). Then in (Housman et al. 2009a), the subject performed reaching task of 12 targets positioned at the edge of the workspace. Targets were defined at different heights; lowest height corresponded to shoulder flexion/extension at 0 degrees. The highest target was 15 cm high from acromion. While in (Iwamuro et al. 2008), the subjects were divided into the two groups, the control group and the other one with T-Wrex. T-Wrex group received assistance from robot during the session and control group received assistance from a trained therapist. A defined set of functionally oriented upper-extremity tasks tailored to each subject's motor abilities, such as moving blocks from one area to another or turning a light switch on and off (Stein et al. 2007). For REHAROB, subject were randomly allocated into two groups control and experimental and both groups received Bobath therapy. The experimental group also received additional 30 min of robot therapy (Fazekas et al. 2007). In the experiments of L-Exos, subjects usually perform three types of movements i-e reaching task, path following, and object manipulation (Frisoli et al. 2008). Then Passive and active therapy was provided. Active therapy included virtual ball catch exercise and labyrinth game

Table 2 Clinical robot-assisted rehabilitation trials

Robotic device	Focus	Intensity	Outcome	Assumptions
T-Wrex (Housman et al. 2007)	Robot-assisted training versus Conventional training	1 h, 3 times/week for 8 or 9 weeks	The subject in both groups showed improvement but a comparison of pre and post treatment FM between groups did show any significant difference	Robot-based training can be as effective as conventional training
Active Joint Brace (Stein et al. 2007)	Effects of EMG based Exoskeletal robotic brace	2–3 h/week, 18 h during 6–9 weeks	All subject reported improvement in FM and MAS. Severely impaired patient was also able to control device with EMG signal	EMG powered device was effective and can improve motor function
REHAROB (Fazekas et al. 2007)	Usefulness of REHAROB	20 sessions of 30 min for both group plus 30 min extra for the experimental group	Both groups showed improvement on all clinical scores	Robot therapy in combination with traditional therapy is useful
L-Exos (Frisoli et al. 2008)	Effects of L-Exos on upper limb rehabilitation	1 h, 3 times/week for 6 weeks	Improvements in FM score (average increment of 4). Improvements in MAS and ROM for elbow and wrist	Upper limb Exoskeleton with VR can help reduce impairments
T-Wrex (Housman et al. 2009a)	Improving reaching workspace with T-Wrex	2 sessions, with 36 trial in a session	Subject's proximity to target reduced and subject can now move 22% closer to target and saw 40% decrease in the average jerk	Improved workspace and smooth movement with T-Wrex based therapy
T-Wrex (Iwamuro et al. 2008)	Robot training by T-Wrex with conventional training	1 h, 3 times/week for 8–9 weeks	Both groups gained improvement in FM, Quality of movement and free reaching ROM. T-Wrex group showed much significant improvement in FM than the control group	Robot-assisted therapy has a slight benefit over conventional training
ARMin I (Nef et al. 2009)	Effects of exoskeleton robot on motor recovery	Subject 1 and 2: 3 1 h session/week Subject 3 has 5 1 h session/week	FM score of all three subjects showed a gain of 3.1, 3 and 4.2 respectively. Active Range of Motion also improved for all the subjects. All subject showed improved performance on coordination test	The exoskeleton robot had a positive effect on the subject's arm movement coordination, functional task, and ROM and muscle strength
ARMin II (Staubli et al. 2009) L-Exos (Frisoli et al. 2012a)	Intensive arm training and motor impairment Evaluating effect of robot-assisted training	Subject 1 and 4: 3 h/week Subject 2 and 3: 4 h/week	The gain in FM and WMFT from baseline to 6 months follow up. This gain suggest that robotic therapy can significantly influence outcome	Intensive task training in effective and can lead to improvement in motor function
		Not available	Improvement in FM from 25.5 ± 12.99 to 31.43 ± 15.41	Improved quality and smoothness of movement and reduced timing
L-Exos (Frisoli et al. 2012b)	Restoration of motor function in spatial reaching movement using exoskeleton	1 h, 3 times/week for 6 weeks	The gain in FM and MAS score. A positive effect in movement execution, smoothness, and range	Improved motor function and reduced spasticity due to robot training

Table 2 (continued)

Robotic device	Focus	Intensity	Outcome	Assumptions
Pneu-Wrex (Reinkensmeyer et al. 2012)	Evaluating assist as needed method to improve upper limb function	1 h, 3 times/week for 8–9 weeks	A significant gain in FM in experimental group over the control group. Similar improvement in NSA and MAL QOM and B&B test	Robotic assistance with Assist as a needed method in the 3D virtual task is more effective than the conventional method
ARMEO Spring (Colomer et al. 2013b)	Armeo Spring based rehabilitation	1 h, 3 times a week for 12 weeks	Analysis of the result showed significant improvement on all clinical scales with a gain in both function and activity scale.	Robotic device is effective even long time after stroke
UL-EXOS7 (Byl et al. 2013)	Compare task-specific training by a robot with training by a physical therapist.	2 session/week for 6 weeks	Significant improvement in FM scores and range of motion for all groups. The robot groups and actual task group achieved similar gains, with no difference between unilateral and bilateral robot group	Intensive task-specific training with robot and without robot achieved similar results
UL-EXOS7 (Kim et al. 2013)	Unilateral vs bilateral training	90 min, 2 times/week for 6 weeks	The unilateral group had improvement in proximal area and the bilateral group had in the distal area. Bilateral improved wrist joint movement, painted area, and efficiency index and unilateral had improvement in travel distance	No significant difference in bilateral and unilateral training method
ARMin III (Klamroth-Marganska et al. 2014)	Effects of task-specific 3D training and its long-term effects on impairment and activities	1 h, 3 times/week for 8 weeks	Higher FMA-UE gains in robot group. Follow up showed that robot group remained fairly stable but those in control showed improvement and their FMA-UE score reached a similar level to that of robot group after 4 weeks	Robotic therapy showed slightly better result however difference between the two methods was not statistically significant
BONES (Milot et al. 2013)	Evaluate the performance of the device in reducing impairment and single joint training versus multiple joint training	1 h, 3 times/week for 8 weeks	No difference between groups except for BBT, grip strength and strength of shoulder. AB approach showed greater carryover effect when analyzed using Hill Armitage approach, however independent *t* test showed no difference between them	Improved motor function by training with exoskeleton but no significant difference between SJT and MJT
GENTLE/G (Loureiro et al. 2014)	Effect of robot-assisted reach and grasp therapy	1 h, 4 times a week for 12 weeks	FMA score for each subject showed improvement. Higher gain in robot-mediated phase in both outcome measure	Robot-mediated therapy with reach and grasp method gave positive results in sub-acute phase

and he training consisted of three parts (reaching, solving cube puzzles and evaluation part) (Frisoli et al. 2012a). The performance was judged based on timing and smoothness. While the training session consisted of goal direct reaching movement performed by the subject (Frisoli et al. 2012b). The first exercise was point reaching task, the second exercise was drawing a circular path in VR and third exercise subject was asked to complete the puzzle using 9 cubes. For the first version ARMin I of the upper limb exoskeleton series ARMin, first few minutes were spent by the therapist to select patient-specific movement using teach-a-repeat procedure (Nef et al. 2009). Then the remaining time was used for active training and the subject with ARMin II (or ARMin II) has to move his limb to catch a ball shown on a video screen (Klamroth-Marganska et al. 2014; Staubli et al. 2009). Subjects were randomly assigned with a ratio of 1:1 to either receive robotic or conventional therapy. Robot group performed three type of activities i–e mobilization, games, and training for ADL. Control group underwent conventional therapy training. For another version ARMEO Spring, the treatment protocol for consisted of 36 intensive therapy sessions. Exercise program was modified by physiotherapist for each patient (Colomer et al. 2013b). For UL-EXOS7, subjects were divided into three groups (actual TSRT, virtual TSRT with unilateral and virtual TSRT with bilateral) based on the type of intervention they would receive (Byl et al. 2013). The virtual task was practiced with UL-Exo7 and the actual task involved trained physical therapist. During the early phase of the study, subject played video with default tasks (flower 30 min, joint movement 15 min, paint 15 min and reach 15 min) (Kim et al. 2013). However, as the study progressed they either played odd games or even games depending on their visit number. In the experiments of BONES, subjects were randomized to either receive single joint training or multiple joint training based on two approaches; AB (single joint first) or BA (multi-joint first) (Milot et al. 2013). SJT consisted of tracking 3D upper limb phantom with 1 DOF actuated at a time. MJT consisted of 40 min of games simulating functional activities and 20 min of SJT. AB-BA crossover design (GENTLE/G) with subject was divided into two groups. Phase A consist of robot therapy in combination with conventional therapy and in phase B subject only received conventional therapy (Loureiro et al. 2014). Table 2 compares the clinical trials with detail information about each study. Table 2 includes information on focus and aim of the experiment, intervention provided during the trial, outcome measure, results and assumptions based on the results.

Seventeen studies met the inclusion criteria, and full articles were downloaded from the electronic resources. Several papers reporting clinical trials of the end-effector based device were rejected based on the exclusion criteria. The papers included in the review reported the results of clinical studies of robot-assisted upper limb rehabilitation using an exoskeleton device. The baseline characteristics of subjects that participated in these studies are given in Table 3.

Seventeen clinical trials have been conducted for upper limb rehabilitation using exoskeleton robot. Three trials were conducted with each of T-Wrex (Iwamuro et al. 2008; Housman et al. 2007, 2009) and L-Exos (Frisoli et al. 2008, 2012b), two trial were conducted with UL-Exo7 (Kim et al. 2013; Byl et al. 2013) and ARMin (Nef et al. 2009; Staubli et al. 2009) and one trial with Armeo Spring (Colomer et al. 2013a), Pneu-Wrex (Reinkensmeyer et al. 2012), ARMin III (Klamroth-Marganska et al. 2014), BONES (Milot et al. 2013), REHAROB (Fazekas et al. 2007), GENTLE/G (Loureiro et al. 2014) and active joint brace system (Stein et al. 2007).

Three clinical trials were conducted with T-Wrex system (Iwamuro et al. 2008; Housman et al. 2007, 2009). These trials produced a positive outcome, as results showed that repetitive training could lead to a reduction in impairment (Housman et al. 2007), improvement in workspace and smoothness of movement (Iwamuro et al. 2008). When analyzed with comparable conventional therapy results showed the only modest difference in favor of T-Wrex assisted therapy. A commercial version of T-Wrex called ARMEO Spring was also tested in a clinical trial (Colomer et al. 2013b). The trial showed that therapy promoted recovery with improvement in function of upper limb and activity scale of upper limb (Colomer et al. 2013b). Three clinical trials were also conducted with L-Exos (Frisoli et al. 2008, 2012a, b). The tasks performed with L-Exos were very similar across three studies. Results showed a reduction in impairment can be achieved with L-Exos (Frisoli et al. 2008, 2012a; b). Other benefits of training with L-Exos were increased in the range of motion (Frisoli et al. 2008), improved smoothness of the movement, increased active joint ROM and decreased the time required to complete the movement (Frisoli et al. 2012b). Two studies compared unilateral and bilateral training method using UL-Exos-7 (Kim et al. 2013; Byl et al. 2013). Both studies did not report any statistically significant difference between the said methods (Kim et al. 2013; Byl et al. 2013). Moreover, it was observed that intensive task training with or without robot reported a similar level of improvement (Byl et al. 2013). ARMin exoskeleton was used in three clinical studies (Milot et al. 2013; Nef et al. 2009; Staubli et al. 2009). A clinical trial of ARMin I and ARMin II were single case studies with only 3 and 4 patients respectively (Nef et al. 2009; Staubli et al. 2009). Meanwhile trial of ARMin III was a randomized controlled trial with 77 stroke patients (Klamroth-Marganska et al. 2014). Results of two single case studies showed that two versions of ARMin Exoskeleton are

Table 3 Baseline characteristics of clinical trail

Robotic device	Number of participants	Stroke stage	Study design	Age (years)	Post-stroke time (months)	Baseline assessment measure
T-Wrex (Housman et al. 2007)	23	Chronic	RCT	56.9 ± 11.1	104 ± 9.9	FM
Active Joint Brace (Stein et al. 2007)	6	Chronic	BA	53	44.04	FM, MAS
REHAROB (Fazekas et al. 2007)	30	Chronic	RCT	CT: 55.9 and RT: 56.2	CT: 9.5 and RT: 23.5	FM (0–36)
L-Exos (Frisoli et al. 2008)	9	Chronic	BA	NA	NA	FM
T-Wrex (Housman et al. 2009a)	10	Chronic	RCT	58 ± 14	42 ± 23	CMSA
T-Wrex (Iwamuro et al. 2008)	28	Chronic	RCT	CT: 56.4 ± 12.8 and RT: 54.2 ± 11.9	CT: 112.4 and RT 84.5	FM
ARMin I (Nef et al. 2009)	3	Chronic	SCS	48, 65 and 55	14,40,25	FM, AS, MRC
ARMin II (Staubli et al. 2009)	4	Chronic	SCS	52.75 ± 9.5	45.25 ± 57.31	FM, WMFT
L-Exos (Frisoli et al. 2012a)	7	Chronic	BA	62.9 ± 9.9	6	FM, MAS
L-Exos (Frisoli et al. 2012b)	9	Chronic	BA	61.4 ± 14.1	36–108	FM, MAS
Pneu-Wrex (Reinkensmeyer et al. 2012)	26	Chronic	RCT	RT: 60 ± 10, CT: 61 ± 13	CT: 67 ± 56 and RT: 65 ± 47	FM, Rancho level, Nottingham sensory
ARMEO Spring (Colomer et al. 2013b)	23	Chronic	SCD	54.9 ± 9.5	10.9 ± 3.0	FM
UL-EXOS7 (Byl et al. 2013)	15	Chronic	RCT	CT: 59.3 ± 6.8, RTU: 54.2 ± 20.5 and RTB: 65.2 ± 5.4	CT: 6.4 ± 4.4; RTU: 10.2 ± 5 RTB: 8.4 ± 4.2	FM
UL-EXOS7 (Kim et al. 2013)	15	Chronic	RCT	NA	NA	FM
ARMin III (Klamroth-Marganska et al. 2014)	77	Chronic	RCT	CT: 58 ± 14 RT: 55 ± 13	CT: 40 ± 45 RT: 52 ± 44	FM, WMFT
BONES (Milot et al. 2013)	20	Chronic	BA	60 ± 7	38 ± 38	FM, Box, and Black, WMFT
GENTLE/G (Loureiro et al. 2014)	4	Sub-Acute	SCS	52.25 ± 7.67	3.75 ± 1.70	FM, MAS

effective with improvement in movement coordination, ROM and strength (Nef et al. 2009; Staubli et al. 2009). A detail RCT with an updated version of ARMin (ARMin III) reported no significant difference between conventional rehabilitation and ARMin assisted training (Klamroth-Marganska et al. 2014). A clinical trial of BONES compared single joint training versus multiple joint training (Milot et al. 2013). The result showed the benefit of training with BONES exoskeleton with improvement in clinical scores; however, no difference was reported between single joint and multiple joint training. A significant difference between conventional and robot-assisted therapy was observed in a clinical trial of Pneu-Wrex, a pneumatically actuated version of T-Wrex (Reinkensmeyer et al. 2012). In this study, subject improved their upper limb with a reduction in impairment with therapy based on an assist as a needed paradigm and 3D virtual tasks (Reinkensmeyer et al. 2012). An EMG based device for elbow joint was tested in an uncontrolled clinical trial. The trial produced comparable results to the other control strategy indicating that EMG based control strategy is as effective as the other control strategy (Stein et al. 2007). A clinical trial of Gentle/G system compared robot-assisted therapy with conventional therapy (Loureiro et al. 2014). Both types of therapy treatments were given to set of patients. Results indicated improvement in both phases, however, gain achieved during the robot phase was higher (Loureiro et al. 2014).

5 Discussion

The performance and the recovery of the patients would suffer if the patient is not motivated and/or satisfied with the robotic rehabilitation. Therefore it is important to consider patient feedback during and after a clinical trial. Only a few clinical studies collected feedback at the end of the clinical trial. An RCT done with T-Wrex collected patient's feedback at the end of the trial in the form of survey (Housman et al. 2009a). The survey showed that 70% patient considered robotic therapy to be more effective and functional. The patient assigned to T-Wrex group considered robot therapy to be less boring but more effective. Around 85% patients in the conventional group also expressed similar views. Patients also gave similar feedback in a study conducted with Pneu-Wrex (Reinkensmeyer et al. 2012). A comparable survey was also conducted with a clinical trial of BONES (Milot et al. 2013). The survey showed that patient appreciated the robotic therapy with 4/5 and 5/5 rating gave by 44% and 38% patients respectively for the improvement in their affected upper limb. When asked about their preference between single joint training versus multiple joint training, over 75% rated both training method equally. This was coherent with clinical results which found no significant difference between them. A questionnaire was used in the clinical study with ARMin II (Staubli et al. 2009). In the questionnaire, the patient reported progress of affected upper extremity. They reported robot therapy to be more encouraging and they were keener to employ their affected arm in way of life. They were able to lift their arm to a higher position as they feel it became lighter and less stiff.

Even though not all clinical trial collected patient feedback at the end of the study, however, an interesting trend appears when feedback was collected (Reinkensmeyer et al. 2012; Milot et al. 2013; Housman et al. 2009a; Staubli et al. 2009). Results indicate that majority of patients enjoyed the robot-aided therapy training and reported it to be fewer boring (Reinkensmeyer et al. 2012; Milot et al. 2013; Housman et al. 2009a). This means that patents are more engaged and motivated during a therapy session. With a high level of motivation, patient is open to performing similar exercise at unsupervised setting such as home (Housman et al. 2009a). This will help in impairment reduction leading to the functional recovery of their impaired arm. Significantly high percentage of patients reported that robot-aided training is more effective and the improvement gained during physical therapy will benefit them during their activities of daily living (Reinkensmeyer et al. 2012; Milot et al. 2013; Housman et al. 2009a; Staubli et al. 2009). Even patients assigned to conventional therapy reported liking for robot-assisted therapy (Housman et al. 2009a). If patients are satisfied with their therapy training then they will use their affected arm more readily in their daily life. This will ensure that their clinical gain is better utilized in daily life. Hence it can be said robot-assisted therapy is an effective method to physical therapy and it keeps patients motivated and engaged.

The first area yet to be investigated in a clinical trial is a comparative study between an end-effector robotic system and an exoskeleton robotic system. Both end-effector robot (Coote et al. 2008; Masiero et al. 2010; Lo et al. 2010; Liao et al. 2012; Bovolenta et al. 2009; Hu et al. 2009) and exoskeleton robot (Furukawa et al. 2017; Frisoli et al. 2012a, b; Reinkensmeyer et al. 2012; Colomer et al. 2013b; Housman et al. 2009a; Nef et al. 2009; Byl et al. 2013) have shown potential to reduce impairments and it is difficult to compare their result as both operate differently. A comprehensive clinical study is required to identify the potential benefits of one device over the other in reducing impairment and improvement in motor function. Future studies could also look at the effectiveness of different control schemes such as comparing Assist-as-needed control with EMG based control or Impedance and Admittance control. At the moment there are no standard guidelines to measure the effectiveness of robotic therapy for stroke patients. Clinical studies have used different devices, training protocols and evaluation criteria to judge the performance of robotic device on impairment reduction. Since every patient's medical condition is different, one training method may be suitable for one patient but inappropriate for others. This can potentially lead to inaccurate results, therefore it is important to develop a standard set of guidelines for providing robot-assisted training. These guidelines must be broad enough to cover various important stages of rehabilitation. Guidelines should cover aspects such therapy exercises/tasks, level and type assistance, the intensity of training, standard clinical tests to measure the evaluations. For any future trial, the number of patients recruited should be high to ensure that level of evidence to support the results must be strong.

6 Conclusion

In past two decades, many robotic devices for upper limb rehabilitation have been developed and tested. This paper has a systematic review on exoskeleton robotic-based upper limb robotic system, including their mechanism design, control strategies and clinical trial performance. These exoskeletons have been used in various clinical studies that measured their effectiveness using various clinical and non-clinical tests. A clinical trial of exoskeleton robots for upper limb revealed positive outcome as this form of therapy can easily match and in many cases produce a better result than conventional therapy. Results also indicated if the patient is active during the therapy session than the reduction in impairment was higher. Therefore exoskeleton with patient-driven control strategy produced significantly better results. Impact of robot-assisted therapy was not just restricted to clinical results. It was found that patient preferred this form of therapy, found it less boring and more effective.

Acknowledgements This research is funded by the National Natural Science Foundation of China (Nos. 51675389 and 51475342), and the Excellent Dissertation Cultivation Funds of Wuhan University of Technology (No. 2016-YS-060).

References

Al-Fahaam, H., Davis, S., Nefti-Meziani, S.: Wrist rehabilitation exoskeleton robot based on pneumatic soft actuators, pp. 491–496. ISCAE, Newcastle upon Tyne (2016)

Anam, K., Al-Jumaily, A.A.: Active exoskeleton control systems: state of the art. Procedia Eng. **41**, 988–994 (2012)

Andrikopoulos, G., Nikolakopoulos, G., Manesis, S.: Design and development of an exoskeletal wrist prototype via pneumatic artificial muscles. Meccanica **50**, 2709–2730 (2015a)

Andrikopoulos, G., Nikolakopoulos, G., Manesis, S.: Motion control of a novel robotic wrist exoskeleton via pneumatic muscle actuators. In: Proc. Emerg. Tech. Fact. Autom., pp. 1–8 (2015b)

Ball, S.J., Brown, I.E., Scott, S.H.: MEDARM: a rehabilitation robot with 5DOF at the shoulder complex. In: Proc 2007 IEEE/ASME international conference on Advanced intelligent mechatronics, pp. 1–6 (2007)

Bertani, R., Melegari, C., De Cola, M.C., Bramanti, A., Bramanti, P., Calabrò, R.S.: Effects of robot-assisted upper limb rehabilitation in stroke patients: a systematic review with meta-analysis. Neurol. Sci. **38**, 1–9 (2017)

Borzelli, D., Pastorelli, S., Burdet, E., D'Avella, A., Gastaldi, L.: Reducing external perturbation proportionally to operator's wrist muscle co-contraction reduces tracking error and energy consumption. Gait Posture **57**, 24 (2017)

Bovolenta, F., Goldoni, M., Clerici, P., Agosti, M., Franceschini, M.: Robot therapy for functional recovery of the upper limbs: a pilot study on patients after stroke. J. Rehabil. Med. **41**, 971–975 (2009)

Bulboacă, A.E., Bolboacă, S.D., Bulboacă, A.C.: Ethical considerations in providing an upper limb exoskeleton device for stroke patients. Med. Hypotheses **101**, 61 (2017)

Bundy, D.T., Souders, L., Baranyai, K., Leonard, L., Schalk, G., Coker, R., et al.: Contralesional brain–computer interface control of a powered exoskeleton for motor recovery in chronic stroke survivors. Stroke **48**, 1908–1915 (2017)

Byl, N.N., Abrams, G.M., Pitsch, E., Fedulow, I., Kim, H., Simkins, M., et al.: Chronic stroke survivors achieve comparable outcomes following virtual task specific repetitive training guided by a wearable robotic orthosis (UL-EXO7) and actual task specific repetitive training guided by a physical therapist. J. Hand Ther. **26**, 343–352 (2013)

Calanca, A., Muradore, R., Fiorini, P.: A review of algorithms for compliant control of stiff and fixed-compliance robots. IEEE/ASME Trans. Mech. **21**, 613–624 (2016)

Chang, W.H., Kim, Y.-H.: Robot-assisted therapy in stroke rehabilitation. J. Stroke **15**, 174–181 (2013)

Colomer, C., Baldovi, A., Torrome, S., Navarro, M.D., Moliner, B., Ferri, J., et al.: Efficacy of Armeo®Spring during the chronic phase of stroke. Study in mild to moderate cases of hemiparesis. In: Eficacia del sistema Armeo®Spring en la fase crónica del ictus. Estudio en hemiparesias leves-moderadas, vol. 28, pp. 261–267 (2013a)

Colomer, C., Baldoví, A., Torromé, S., Navarro, M.D., Moliner, B., Ferri, J., et al.: Efficacy of Armeo®Spring during the chronic phase of stroke. Study in mild to moderate cases of hemiparesis. Neurologia **28**, 261–267 (2013b)

Coote, S., Murphy, B., Harwin, W., Stokes, E.: The effect of the GENTLE/s robot-mediated therapy system on arm function after stroke. Clin. Rehabil. **22**, 395–405 (2008)

Fazekas, G., Horvath, M., Troznai, T., Toth, A.: Robot-mediated upper limb physiotherapy for patients with spastic hemiparesis: a preliminary study. J. Rehabil. Med. **39**, 580–582 (2007)

Formaggio, E., Storti, S.F., Galazzo, I.B., Gandolfi, M., Geroin, C., Smania, N., et al.: Time–frequency modulation of ERD and EEG coherence in robot-assisted hand performance. Brain Topogr. **28**, 352–363 (2015)

Frisoli, A., Borelli, L., Montagner, A., Marcheschi, S., Procopio, C., Salsedo, F., et al.: Arm rehabilitation with a robotic exoskeleleton in virtual reality. In: Proceeding Noordwijk, pp. 631–642 (2007)

Frisoli, A., Borelli, L., Montagner, A., Marcheschi, S., Procopio, C., Salsedo, F., et al.: Robot-mediated arm rehabilitation in Virtual Environments for chronic stroke patients: a clinical study. In: ICRA 2008. IEEE international conference on robotics and automation, pp. 2465–2470 (2008a)

Frisoli, A., Chisari, C., Sotgiu, E., Procopio, C., Fontana, M., Rossi, B., et al.: Rehabilitation training and evaluation with the L-EXOS in chronic stroke, vol. 7251, pp. 242–245. Springer, Berlin (2012a)

Frisoli, A., Procopio, C., Chisari, C., Creatini, I., Bonfiglio, L., Bergamasco, M., et al.: Positive effects of robotic exoskeleton training of upper limb reaching movements after stroke. J. Neuro Eng. Rehab **9**, 36 (2012b)

Furukawa, J.I., Noda, T., Teramae, T., Morimoto, J.: Human movement modeling to detect biosignal sensor failures for myoelectric assistive robot control. IEEE Trans. Robot. **33**, 846–857 (2017)

Go, A.S., Mozaffarian, D., Roger, V.L., Benjamin, E.J., Berry, J.D., Borden, W.B., et al.: Executive summary: heart disease and stroke statistics—2016 update a report from the American Heart Association. Circulation **133**, 447–554 (2016)

Gopura, R.A.R.C., Kiguchi, K.: Mechanical designs of active upper-limb exoskeleton robots state-of-the-art and design difficulties, pp. 178–187. Kyoto, ICORR (2009)

Gopura, R.A.R.C., Kiguchi, K. and Li, Y.: SUEFUL-7: A 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control. In: Processing on Intelligent Robots and System St. Louis, MO, pp. 1126–1131 (2009)

Gopura, R.A.R.C., Bandara, D.S.V., Kiguchi, K., Mann, G.K.I.: Developments in hardware systems of active upper-limb exoskeleton robots: a review. Robot. Auton. Syst. **75**, 203–220 (2016)

Housman, S.J., Le, V., Rahman, T., Sanchez, R.J., Reinkensmeyer, D.J.: Arm-training with T-WREX after chronic stroke: preliminary results of a randomized controlled trial. In: Proc ICORR 2007. IEEE 10th international conference on rehabilitation robotics, pp. 562–568 (2007)

Housman, S.J., Scott, K.M., Reinkensmeyer, D.J.: A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehab. Neural., Re (2009a)

Housman, S.J., Scott, K.M., Reinkensmeyer, D.J.: A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabil. Neural Repair **23**, 505–514 (2009b)

Hu, X.L., Tong, K.Y., Song, R., Zheng, X.J., Lui, K.H., Leung, W.W.F., et al.: Quantitative evaluation of motor functional recovery process in chronic stroke patients during robot-assisted wrist training. J. Electromyogr. Kines **19**, 639–650 (2009)

Huang, J., Tu, X., He, J.: Design and evaluation of the RUPERT wearable upper extremity exoskeleton robot for clinical and in-home therapies. IEEE. T. Syst. Man Cybern. Syst. **46**, 926–935 (2016)

Huysamen, K., Bosch, T., Looze, M.D., Stadler, K.S., Graf, E., O'Sullivan, L.W.: Evaluation of a passive exoskeleton for static upper limb activities. Appl. Ergon. **70**, 148–155 (2018)

Iwamuro, B.T., Cruz, E.G., Connelly, L.L., Fischer, H.C., Kamper, D.G.: Effect of a gravity-compensating orthosis on reaching after stroke: evaluation of the therapy assistant WREX. Arch. Phys. Med. Rehab. **89**, 2121–2128 (2008)

Jamwal, P.K., Hussain, S., Ghayesh, M.H., Rogozina, S.V.: Impedance control of an intrinsically compliant parallel ankle rehabilitation robot. IEEE. T. Ind. Electron. **63**, 3638–3647 (2016)

Keemink, A., Van, G.O., Wessels, M., Stienen, A.: Differential inverse kinematics of a redundant 4R exoskeleton shoulder joint. IEEE. T. Neural Syst. Rehab. Eng. **26**, 1 (2018)

Kim, H., Miller, L.M., Fedulow, I., Simkins, M., Abrams, G.M., Byl, N., et al.: Kinematic data analysis for post-stroke patients following bilateral versus unilateral rehabilitation with an upper limb wearable robotic system. IEEE Trans. Neural Syst. Rehab. Eng. **21**, 153–164 (2013)

Klamroth-Marganska, V., Blanco, J., Campen, K., Curt, A., Dietz, V., Ettlin, T., et al.: Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. Lancet Neurol. **13**, 159–166 (2014)

Krebs, H.I., Ferraro, M., Buerger, S.P., Newbery, M.J., Makiyama, A., Sandmann, M., et al.: Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus. J. Neuroeng. Rehab. **1**, 5 (2004)

Lee, K.M., Guo, J.: Kinematic and dynamic analysis of an anatomically based knee joint. J. Biomech. **43**, 1231–1236 (2010)

Li, X., Pan, Y., Chen, G., Yu, H.: Multi-modal control scheme for rehabilitation robotic exoskeletons. Int. J. Robot. Res. **36**, 759–777 (2017)

Li, Z., Huang, B., Ajoudani, A., Yang, C., Su, C.Y., Bicchi, A.: Asymmetric bimanual control of dual-arm exoskeletons for human-cooperative manipulations. IEEE Trans. Robot. **34**, 264–271 (2018)

Liao, W.W., Wu, C.Y., Hsieh, Y.W., Lin, K.C., Chang, W.Y.: Effects of robot-assisted upper limb rehabilitation on daily function and real-world arm activity in patients with chronic stroke: a randomized controlled trial. Clin. Rehabil. **26**, 111–120 (2012)

Lo, H.S., Xie, S.Q.: Exoskeleton robots for upper-limb rehabilitation: state of the art and future prospects. Med. Eng. Phys. **34**, 261–268 (2012)

Lo, A.C., Guarino, P.D., Richards, L.G., Haselkorn, J.K., Wittenberg, G.F., Federman, D.G., et al.: Robot-assisted therapy for long-term upper-limb impairment after stroke. New Engl. J. Med. **362**, 1772–1783 (2010)

Lopez, A.D., Mathers, C.D., Ezzati, M., Jamison, D.T., Murray, C.J.: Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. Lancet **367**, 1747–1757 (2006)

Loureiro, R.C., Harwin, W.S., Lamperd, R., Collin, C.: Evaluation of reach and grasp robot-assisted therapy suggests similar functional recovery patterns on proximal and distal arm segments in sub-acute hemiplegia. IEEE Trans. Neural Syst. Rehabil. Eng. **22**, 593–602 (2014)

Lum, P.S., Burgar, C.G., Van der Loos, M., Shor, P.C.: The MIME robotic system for upper-limb neuro-rehabilitation: results from a clinical trial in subacute stroke. In: Proceeding international conference on rehabilitation robotics, pp. 511–514 (2005)

Madani, T., Daachi, B., Djouani, K.: Modular-controller-design-based fast terminal sliding mode for articulated exoskeleton systems. IEEE. T. Contr. Syst. T. **25**, 1–8 (2017)

Masiero, S., Armani, M., Chiasera, A., Ferlini, G., Ferraro, C., Rosati, G.: Post-stroke robotic training of the upper limb: a randomized trial study. Pm&R **2**, S2–S3 (2010)

Meng, W., Liu, Q., Zhou, Z., Ai, Q., Sheng, B., Xie, S.: Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation. Mechatronics **31**, 132–145 (2015)

Milot, M.-H., Spencer, S.J., Chan, V., Allington, J.P., Klein, J., Chou, C., et al.: A crossover pilot study evaluating the functional outcomes of two different types of robotic movement training in chronic stroke survivors using the arm exoskeleton BONES. J. Neuroeng. Rehab. **10**, 112 (2013)

Mushage, B.O., Chedjou, J.C., Kyamakya, K.: Fuzzy neural network and observer-based fault-tolerant adaptive nonlinear control of uncertain 5-DOF upper-limb exoskeleton robot for passive rehabilitation. Nonlinear Dynam. **87**, 2021–2037 (2017)

Nef, T., Quinter, G., Müller, R., Riener, R.: Effects of arm training with the robotic device ARMin I in chronic stroke: three single cases. Neurodegen. Dis. **6**(5–6), 240–251 (2009)

Nef, T., Guidali, M., Riener, R.: ARMin III—arm therapy exoskeleton with an ergonomic shoulder actuation. Appl Bionics. Biomech. **6**, 127–142 (2015)

Nichols, M., Townsend, N., Luengo-Fernandez, R., Leal, J., Gray, A., Scarborough, P., Rayner, M.: European Cardiovascular Disease Statistics 2012. European Heart Network, Brussels, European Society of Cardiology, Sophia Antipolis (2012)

Niyetkaliyev, A.S., Hussain, S., Ghayesh, M.H., Alici, G.: Review on design and control aspects of robotic shoulder rehabilitation orthoses. IEEE Trans. Hum. Mach. Syst. **47**, 1–12 (2017)

Oguntosin, V.W., Mori, Y., Kim, H., Nasuto, S.J., Kawamura, S., Hayashi, Y.: Design and validation of exoskeleton actuated by soft modules toward neurorehabilitation-vision-based control for precise reaching motion of upper limb. Front. Neurosci. **11**, 352 (2017)

Perry, J.C., Rosen, J., Burns, S.: Upper-limb powered exoskeleton design. IEEE/ASME Trans. Mech. **12**, 408–417 (2007)

Poli, P., Morone, G., Rosati, G., Masiero, S.: Robotic technologies and rehabilitation: new tools for stroke patients' therapy. Biomed. Res. Int. (2013). https://doi.org/10.1155/2013/153872

Reinkensmeyer, D.J., Kahn, L.E., Averbuch, M., McKenna-Cole, A., Schmit, B.D., Zev, W.: Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide. J. Rehabil. Res. Dev. **37**, 653–662 (2000)

Reinkensmeyer, D.J., Wolbrecht, E.T., Chan, V., Chou, C., Cramer, S.C., Bobrow, J.E.: Comparison of three-dimensional, assist-as-needed robotic arm/hand movement training provided with Pneu-WREX to conventional tabletop therapy after chronic stroke. Am. J. Phys. Med. Rehabil. **91**, S232–S241 (2012)

Staubli, P., Nef, T., Klamroth-Marganska, V., Riener, R.: Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: four single-cases. J. NeuroEng. Rehabil. **6**, 46 (2009)

Stein, J., Narendran, K., McBean, J., Krebs, K., Hughes, R.: Electromyography-controlled exoskeletal upper-limb-powered orthosis for exercise training after stroke. Am. J. Phys. Med. Rehab. **86**, 255–261 (2007)

Stroke Foundation of New-Zealand: Understanding and preventing stroke and transient ischaemic attack. http://www.stroke.org.nz/stroke-facts-and-fallacies

Townsend, N., Wickramasinghe, K., Bhatnagar, P., Smolina, K., Nichols, M., Leal, J., Luengo-Fernandez, R., Rayner, M.: Coronary heart disease statistics 2012 edition. British Heart Foundation, London (2012)

Treadway, E., Gan, Z., Remy, C.D., Gillespie, R.B.: Toward controllable hydraulic coupling of joints in a wearable robot. IEEE Trans. Robot. **34**, 1–16 (2018)

Tsugawa, Y., Kumamaru, H., Yasunaga, H., Hashimoto, H., Horiguchi, H., Ayanian, J.Z.: The association of hospital volume with mortality and costs of care for stroke in Japan. Med. Care **51**, 782–788 (2013)

Ullauri, J.B., Peternel, L., Ugurlu, B., Yamada, Y., Morimoto, J: On the EMG-based torque estimation for humans coupled with a force-controlled elbow exoskeleton. In: Proc international conference on advanced robotics, pp. 302–307 (2015)

Van der Linde, R.Q., Lammertse, P., Frederiksen, E. and Ruiter, B.: The HapticMaster, a new high-performance haptic interface. In: Proc. Eurohaptics, pp. 1–5. (2002)

Veale, A.J., Xie, S.Q.: Towards compliant and wearable robotic orthoses: a review of current and emerging actuator technologies. Med. Eng. Phys. **38**, 317 (2016)

Wan, S., Yang, M., Xi, R., Wang, X., Qian, R. and Wu, Q.: Design and control strategy of humanoid lower limb exoskeleton driven by pneumatic artificial muscles. In: Proc. Int. Conf. M2VIP., Nanjing, China, pp. 1–5 (2016)

Wu, Q., Wang, X., Chen, B., Wu, H.: Development of an RBFN-based neural-fuzzy adaptive control strategy for an upper limb rehabilitation exoskeleton ☆. Mechatronics **53**, 85–94 (2018)

Young, A., Ferris, D.: State-of-the-art and future directions for robotic lower limb exoskeletons. IEEE. Trans. Neural Syst. Rehab. Eng. **25**, 171–182 (2017)

Naqash Rehmat is currently a PhD student of Department of Mechanical Engineering, The University of Auckland, Auckland, New Zealand.

Jie Zuo is a PhD student with successive Graduate and Doctoral Programs at Wuhan University of Technology, China. Her research interests include soft actuator modelling and rehabilitation robot control. She was a receipt of the Best Paper Award at the 12th Chinese Conference on Intelligent Robotics.

Wei Meng received his Ph.D. degree jointly trained by Wuhan University of Technology, China and The University of Auckland, New Zealand from 2012 to 2016. Since November 2017 he has been a Research Fellow in the School of Electronic and Electrical Engineering, University of Leeds, UK. He is also a Lecturer with the School of Information Engineering, Wuhan University of Technology, China. His research interests include robot-assisted rehabilitation, human–robot interaction, and iterative learning control. He has co-authored 3 books, published more than 40 academic journal and conference papers, and hold 3 patents.

Quan Liu received her Ph.D. degree in 2003 from Wuhan University of Technology, China, where she is currently a Chair Professor in Information Science. During the recent five years, she authored over 60 technical publications, proceedings, editorials, and books. She has directed more than 20 research projects. Her research interests include signal processing, embedded systems, robots and electronics. Prof. Liu obtained 2 national awards and 3 provincial and ministerial awards.

Sheng Q. Xie received his Ph.D. degrees from Huazhong University of Science and Technology, China and University of Canterbury, New Zealand, in 1998 and 2002, respectively. He joined University of Auckland in 2003 and became a Chair Professor in (bio)mechatronics in 2011. Since 2017 he has been the Chair Professor in Robotics and Autonomous Systems at the University of Leeds. He has published 7 books, 15 book chapters, and over 400 international journal and conference papers. His current research interests are medical and rehabilitation robots, advanced robot control. Prof. Xie is an elected Fellow of The Institution of Professional Engineers New Zealand (FIPENZ).

Hui Liang received his Ph.D. degree from Beihang University, China in 2006. He is an Associate Professor with the College of Electromechanical Engineering, Qingdao University of Science and Technology, China. His research interests include industrial robot and parallel mechanism. He has published more than 20 academic journal and conference papers, and hold 21 patents.