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Upper Limb Rehabilitation using Robotic Exoskeleton Systems: A Systematic Review

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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.

Index Terms—Robot-assisted rehabilitation, Upper limb exoskeleton, Clinical trials

I. INTRODUCTION

Stroke is one of the major health care issues in the United States [1], Japan [2], UK [3], European Union [4], Australia, New Zealand [5], and rest of the world [6]. In the United States, it is the second biggest cause of death and major cause of adult disability [5]. 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 [7]. 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 [6, 8]. 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

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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[9]. 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 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 [10], MIME [11], ARM Guide [12], Bi-Manu-Track [13] and Gentle/s system [14]. 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 [15], ARMin III [16], CADEN [17], RUPERT[18]. The robotic systems used for upper limb rehabilitation can be studied based on their mechanical structure, control system, and clinical applications. The mechanical configuration [8, 19-27]and control systems[28-36] have been reviewed previously. A detailed insight on various end effector based system and their application in stroke rehabilitation have also been carried out [37]. Gopura *et.al* 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 [38]. Chang *et.al* reviewed various end effector and exoskeleton based clinical studies [39]. 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. Section II and III clarifies upper limb exoskeletons with various mechanical structures and their control strategies. In Section IV, clinical trial performance of these exoskeletons are introduced and compared. Section V discusses and analyses the research limitations and future directions. Finally, conclusions are drawn in Section VI.

II. MECHANICAL DESIGN

The human upper limb is a complex area with three different movement complex; shoulder complex, elbow complex, and wrist joint complex [40, 41]. With these three-movement complexes, the upper limb has total 9 degrees of freedom [42]. The shoulder joint effectively has 5 degrees of freedom, three degrees due to Glenohumeral joint and 2 degrees due to sternoclavicular joint[42]. 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 two 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 [16, 25, 34, 43-52]. Only a few devices provide additional actuation for the forearm, wrist and sternoclavicular joints [53]. Only one exoskeleton (UL-EXO7[54, 55]) out of ten used in clinical trials support seven degrees of freedom, the remaining only provides assistance at the shoulder (3DOF) and elbow joint (1DOF) [43, 46-52, 54, 56-64]. 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[23, 42]. 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 [34, 65-69]. 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 [43, 58, 70], UL-Exo7 [54, 55], GENTLE/G [50], REHAROB [57] and ARMin [34, 49, 62, 63] are actuated using motors (Fig.1). Pneu-Wrex [71] and BONES [49] are based on pneumatic muscles,

as shown in Fig.1 (f). T-Wrex and its commercial version ARMEO Spring only provides gravity support to the whole arm with no robotic actuation [52, 60, 72, 73] in Fig.1 (g). TABLE I provides the detail of the studies undertaken 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.

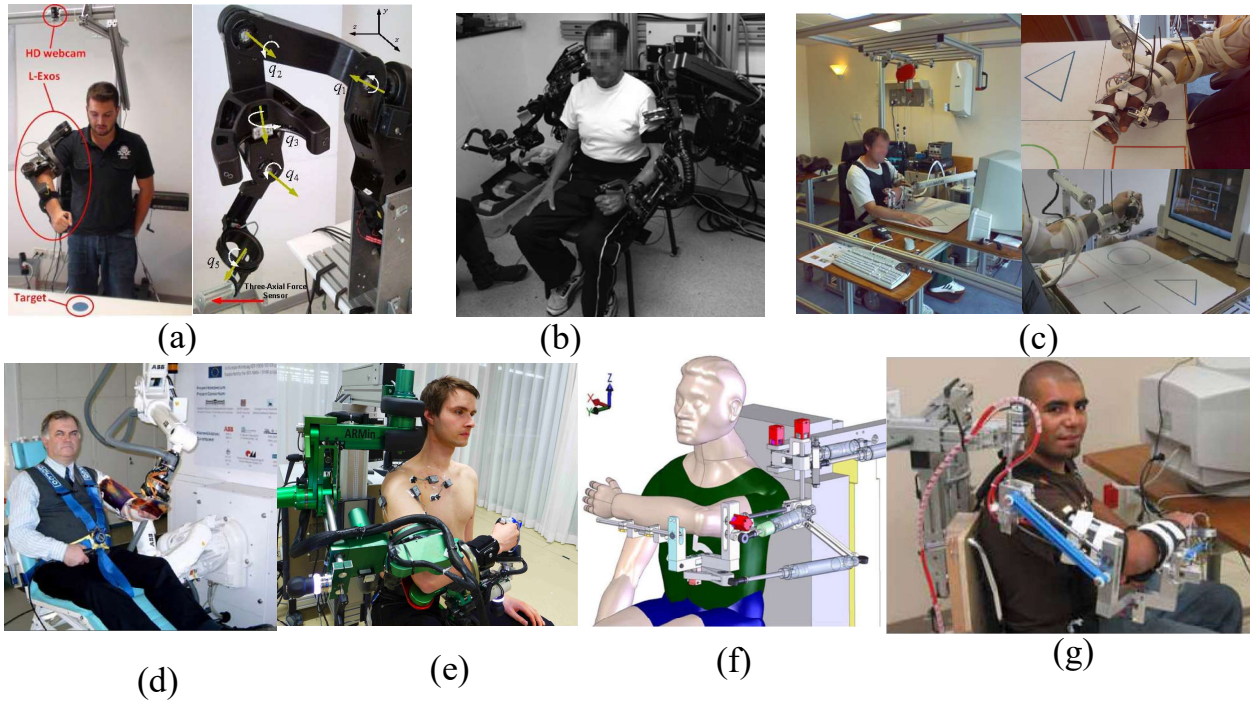


Fig.1. Upper limb rehabilitation exoskeleton (a-g) is reprinted from [43, 50, 55, 57, 63, 71, 73] respectively.

III. 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 effectiveness of active and passive control strategies have analyzed in various exoskeleton robots[43, 46-52, 54, 56-64], as shown in TABLE I.

Patient-driven (Passive) control strategy was tested in a clinical trial of REHAROB [57]. 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) [52, 56, 60, 61], L-Exos [43, 46, 59], ARMin [49, 62, 63], UL-Exo7 [54, 64], BONES [49], Pneu-Wrex [47], AJB [74] and Gentle/G [50]. T-Wrex therapy system delivers rehabilitation training by providing the gravity compensation to entire arm [56, 60, 61]. 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 [56, 60, 61]. This result was further verified in a clinical trial of ARMEO Spring (A commercial version of T-Wrex) [52]. In L-Exos, the patient-driven strategy was implemented through impedance control to provide guided assistance [43, 46, 59]. 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 [43, 46, 59]. In UL-Exo7, the patient-driven strategy is implemented with an admittance control [54, 64]. 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 [54, 64]. The ARMin [49, 62, 63] and Gentle/G system [50] 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 [49, 62, 63]. The Gentle/G provides gravity compensation using a pulley system and support 3 DOF movements through haptic master robot [75]. 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 [75]. 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 [74]. 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 [43, 46-52, 54, 56-64, 74]. Assist as needed (AAN) strategy was implemented in Pneu-Wrex [47] and BONES [49]. 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 [47]. 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.

TABLE I
EXOSKELETONS AND THEIR CONTROL STRATEGIES

Exoskeleton	Actuated DOF	Actuators	Control Strategy	In Comparison to Conventional therapy
T-Wrex[56, 60, 61]	5 DOF	LP	Patient-driven with gravity compensation	Effective
Active Joint Brace[69, 74]	1 DOF	EM	Patient-Driven with EMG signals	Effective
REHAROB[57]	3 DOF	EM	Robot-driven	Comparable
L-Exos[43, 46, 59]	5 DOF	EM	Patient-driven with impedance control	Effective
ARMin[51, 62, 63]	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[71]	4 DOF	PMA	Patient-driven with Assist-as-needed	Effective
ARMEO Spring[52]	5 DOF	LP	Patient-driven with gravity compensation	Effective
UL-EXO7[54, 64]	7 DOF	EM	Robot-driven with admittance control	Effective
BONES[49]	4 DOF	PMA	Patient-driven with AAN.	Effective
Gentle/G[76]	3 Active and 3 passive DOF	LP and EM	Robot and patient-driven with gravity compensation	Effective
T-Wrex[56, 60, 61]	5 DOF	LP	Patient-driven with gravity compensation	Effective
Active Joint Brace[74]	1 DOF	EM	Patient-Driven with EMG signals	Effective

LP = Linear Spring, EM = Electric motor, PMA= Pneumatic muscle actuators

IV. 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 II. 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 [8, 22, 50, 51, 57, 71-73]. Another studies looked at the effects of the individual robotic device on upper limb rehabilitation following stroke [35, 43, 46, 48, 49, 58, 60, 62, 63]. Two studies compared the bilateral training method with unilateral training using exoskeleton device [54, 55]. One study focused on effects of EMG based exoskeleton device for upper limb rehabilitation [77]. 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 [56, 71]. Then in [61], 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 15cm high from acromion. While in [60], 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 [74]. 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 minutes of robot therapy [57]. In the experiments of L-Exos, subjects usually perform three types of movements i-e reaching task, path following, and object manipulation [59]. Then Passive and active therapy was provided. Active therapy included virtual ball catch exercise and labyrinth game and he training consisted of three parts (reaching, solving cube puzzles and evaluation part) [43];. The performance was judged based on timing and smoothness. While the training session consisted of goal direct reaching movement performed by the subject [46]. 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 [62]. 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 [51, 78]. 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 [52]. 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 [64]. 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 minutes, joint movement- 15 minutes, paint-15 minutes and reach-15 minutes) [54]. 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) [49]. SJT consisted of tracking 3D upper limb phantom with one DOF actuated at a time. MJT consisted of 40 minutes of games simulating functional activities and 20 minutes 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 [76]. TABLE II compares the clinical trials with detail information about each study. TABLE II includes information on focus and aim of the experiment, intervention provided during the trial, outcome measure, results and assumptions based on the results.

TABLE II
CLINICAL ROBOT-ASSISTED REHABILITATION TRIALS

Robotic device	Focus	Intensity	Outcome	Assumptions
T-Wrex[56]	Robot-assisted training versus Conventional training	1 hour, 3 times per week for eight or nine 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[74]	Effects of EMG based Exoskeletal robotic brace	2-3 hours per week, 18 hours 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[57]	Usefulness of REHAROB	20 sessions of 30 minutes for both group plus 30 minutes extra for the experimental group.	Both groups showed improvement on all clinical scores.	Robot therapy in combination with traditional therapy is useful
L-Exos[59]	Effects of L-Exos on upper limb rehabilitation	1 hour, 3 times per week for six 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[61]	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[60]	Robot training by T-Wrex with conventional training	1 hour, 3 times per week for 8 to 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[62]	Effects of exoskeleton robot on motor recovery	Subject 1 and 2: 3 one hour session per week Subject 3 has 5 one hour session per 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[78]	Intensive arm training and motor impairment Evaluating effect of	Subject 1 and 4:3 hour per week Subject 2 and 3: 4	The gain in FM and WMFT from baseline to 6 months follow up. This gain suggest that robotic	Intensive task training in effective and can lead to improvement in motor

L-Exos[43]	robot-assisted training	hours per week Not available	therapy can significantly influence outcome Improvement in FM from 25.5 ±12.99 to 31.43 ±15.41.	function. Improved quality and smoothness of movement and reduced timing.
L-Exos[46]	Restoration of motor function in spatial reaching movement using exoskeleton	1 hour, 3 times per week for six 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.
Pneu-Wrex[47]	Evaluating assist as needed method to improve upper limb function	1 hour, 3 times per 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[52]	Armeo Spring based rehabilitation	1 hour, 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[64]	Compare task-specific training by a robot with training by a physical therapist.	2 session per 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[54]	Unilateral v Bilateral training	90 minutes, 2 times per 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[51]	Effects of task-specific 3D training and its long-term effects on impairment and activities	1 hour, 3 times per 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[49]	Evaluate the performance of the device in reducing impairment and single joint training versus multiple joint training.	1 hour, 3 times per week for eight 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[76]	Effect of robot-assisted reach and grasp therapy	1 hour, 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.

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 III.

TABLE III
BASELINE CHARACTERISTICS OF CLINICAL TRIAL

Robotic device	Number of Participants	Stroke Stage	Study Design	Age (yrs.)	Post-stroke Time (months)	Baseline Assessment Measure
T-Wrex[56]	23	Chronic	RCT	56.9±11.1	104±9.9	FM
Active Joint Brace[74]	6	Chronic	BA	53	44.04	FM, MAS
REHAROB[57]	30	Chronic	RCT	CT : 55.9 and RT : 56.2	CT:9.5 and RT 23.5	FM (0-36)
L-Exos[59]	9	Chronic	BA	NA	NA	FM
T-Wrex[61]	10	Chronic	RCT	58±14	42±23	CMSA
T-Wrex[60]	28	Chronic	RCT	CT : 56.4 ± 12.8 and RT :54.2 ± 11.9	CT:112.4 and RT 84.5	FM
ARMin I[62]	3	Chronic	SCS	48, 65 & 55	14,40,25	FM, AS, MRC
ARMin II[78]	4	Chronic	SCS	52.75±9.5	45.25±57.31	FM, WMFT
L-Exos[43]	7	Chronic	BA	62.9±9.9	6	FM, MAS
L-Exos[46]	9	Chronic	BA	61.4 ± 14.1	36-108	FM, MAS
Pneu-Wrex[47]	26	Chronic	RCT	RT: 60±10, CT:61±13	CT: 67±56 and RT: 65±47	FM, Rancho level, Nottingham Sensory
ARMEO Spring[52]	23	Chronic	SCD	54.9±9.5	10.9±3.0	FM
UL-EXOS7[64]	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[54]	15	Chronic	RCT	NA	NA	FM
ARMin III[51]	77	Chronic	RCT	CT: 58 ±14 RT: 55 ± 13	CT: 40 ±45 RT: 52 ± 44	FM, WMFT
BONES[49]	20	Chronic	BA	60±7	38±38	FM, Box, and Black, WMFT
GENTLE/G[76]	4	Sub-Acute	SCS	52.25±7.67	3.75±1.70	FM, MAS

Seventeen clinical trials have been conducted for upper limb rehabilitation using exoskeleton robot. Three trials were conducted with each of T-Wrex [60, 72, 73] and L-Exos [43, 58, 70], two trial were conducted with UL-Exo7 [54, 55] and ARMin [62, 63] and one trial with Armeo Spring [48], Pneu-Wrex [71], ARMin III [51], BONES [49], REHAROB [57], GENTLE/G [50] and active joint brace system [77].

Three clinical trials were conducted with T-Wrex system[60, 72, 73]. These trials produced a positive outcome, as results showed that repetitive training could lead to a reduction in impairment[72], improvement in workspace and smoothness of

movement[60]. 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[52]. The trial showed that therapy promoted recovery with improvement in function of upper limb and activity scale of upper limb[52]. Three clinical trials were also conducted with L-Exos[43, 58, 70]. The tasks performed with L-Exos were very similar across three studies. Results showed a reduction in impairment can be achieved with L-Exos[43, 58, 70]. Other benefits of training with L-Exos were increased in the range of motion [58], improved smoothness of the movement, increased active joint ROM and decreased the time required to complete the movement [70]. Two studies compared unilateral and bilateral training method using UL-Exos-7[54, 55]. Both studies did not report any statistically significant difference between the said methods[54, 55]. Moreover, it was observed that intensive task training with or without robot reported a similar level of improvement [55]. ARMin exoskeleton was used in three clinical studies[49, 62, 63]. A clinical trial of ARMin I and ARMin II were single case studies with only 3 and 4 Patients respectively[62, 63]. Meanwhile trial of ARMin III was a randomized controlled trial with 77 stroke patients[51]. Results of two single case studies showed that two versions of ARMin Exoskeleton are effective with improvement in movement coordination, ROM and strength [62, 63]. A detail RCT with an updated version of ARMin (ARMin III) reported no significant difference between conventional rehabilitation and ARMin assisted training[51]. A clinical trial of BONES compared single joint training versus multiple joint training [49]. 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[71]. 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[71]. 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 [74]. A clinical trial of Gentle/G system compared robot-assisted therapy with conventional therapy [50]. 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 [50].

V. 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 [61]. 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 [47]. A comparable survey was also conducted with a clinical trial of BONES [49]. 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[63]. 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 [47, 49, 61, 63]. Results indicate that majority of patients enjoyed the robot-aided therapy training and reported it to be fewer boring[47, 49, 61]. 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 [61]. 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[47, 49, 61, 63]. Even patients assigned to conventional therapy reported liking for robot-assisted therapy[61]. 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[14, 79-83] and exoskeleton robot [24, 43, 46, 47, 52, 61, 62, 64] 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.

VI. 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.

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