State of the Art Robotic Devices for Wrist Rehabilitation: Design and Control Aspects

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***Abstract*—Robot assisted physical therapy of the upper limb is becoming popular among the rehabilitation community. The wrist is the second most complicated joint in the upper limb after shoulder in terms of degrees of freedom. Several robotic devices have been developed during the past three decades for wrist joint rehabilitation. Intensive physical therapy and repetitive self-practice, with objective measurement of performance could be provided by using these wrist rehabilitation robots at a low cost. There has been an increasing trend in the development of wrist rehabilitation robots to provide safe and customized therapy according to the disability level of patients. The mechanical design and control paradigms are two active fields of research undergoing rapid developments in the field of robot assisted wrist rehabilitation. The mechanical design of these robots could be divided into the categories of end-effector based robots and wearable robotic orthoses. The control for these wrist rehabilitation robots could also be divided into the conventional trajectory tracking control mode and the Assist-as-Needed control mode for providing customized robotic assistance. This paper presents a review of the mechanical design and control aspects of wrist rehabilitation robots. Experimental evaluations of these robots with healthy and neurologically impaired are also discussed along with the future directions of research in the design and control domains of wrist rehabilitation robots.**

***Index Terms*—Actuation, control paradigm, mechanical design, rehabilitation robot, stroke, wrist orthosis.**

I. INTRODUCTION

STROKE and acquired brain injury frequently result in wrist and hand functional movement disorders. Wrist disorders are common in stroke survivors and more than 90% of these survivors require wrist physical therapy [1] in the United States. Wrist therapy is provided so that these stroke survivors can regain functional movement to perform activities of daily living (ADL). The Conventional method of rehabilitating the wrist movement functions is manual physical therapy [2]. Repetitive manual physical therapy has yielded positive outcomes for stroke survivors. However, extensive time from allied health professionals is required to provide manual physical therapy to such a large number of stroke survivors. Also, the physical therapy requires repetitive, task oriented and prolonged training sessions for each stroke survivor. Moreover, the manual process is mainly based on the physical therapists' judgment and there is no objective method of recording and tracking recovery patterns.

To overcome the limitations of manual physical therapy of stroke survivors, several robotic solutions have been presented during the past three decades both for upper [3] and lower limb rehabilitation [4-6]. These robots are capable of providing repetitive, task oriented, intensive and economically viable prolonged therapy sessions. Moreover, the robotic instrumentation can keep track of the patients' kinematic and kinetic parameters which can aid in objective assessment of patients' progress and recovery. Also, the level of assistance provided to the patients can be adjusted by using the robot control paradigms for providing customized robotic rehabilitation.

Wrist rehabilitation robots can be divided into two main categories. The first category is end-effector robotic devices which are based on the traditional robotic manipulators. The patient's hand grasps a robotic end-effector which provide motions to the wrist joint. The second category is based on the concept of orthoses in which the patients' anatomical joints correspond to the robotic orthosis joints. These robotic orthoses are wearable and work in close conjunction with the patients' wrist joint. Several end-effector based as well as orthoses-based wrist rehabilitation robot mechanisms have been designed and presented in literature [7-10]. Also, different control paradigms have been designed and implemented for these end-effector based and orthoses-based wrist rehabilitation robots.

This paper presents a review on the mechanical design and control paradigms of these end-effector based and orthoses-based wrist rehabilitation robots. A Scopus database search has been conducted with the keywords of "*robotic orthosis for wrist rehabilitation*", "*robot for upper limb rehabilitation*" and "*control of upper limb rehabilitation robot*". Initially, 319 papers have been found after this first round of search. After the final round of selection, 72 journal papers have been included in the review. Three exclusions have been made in this review. Passive orthoses without any mechanical actuator are not

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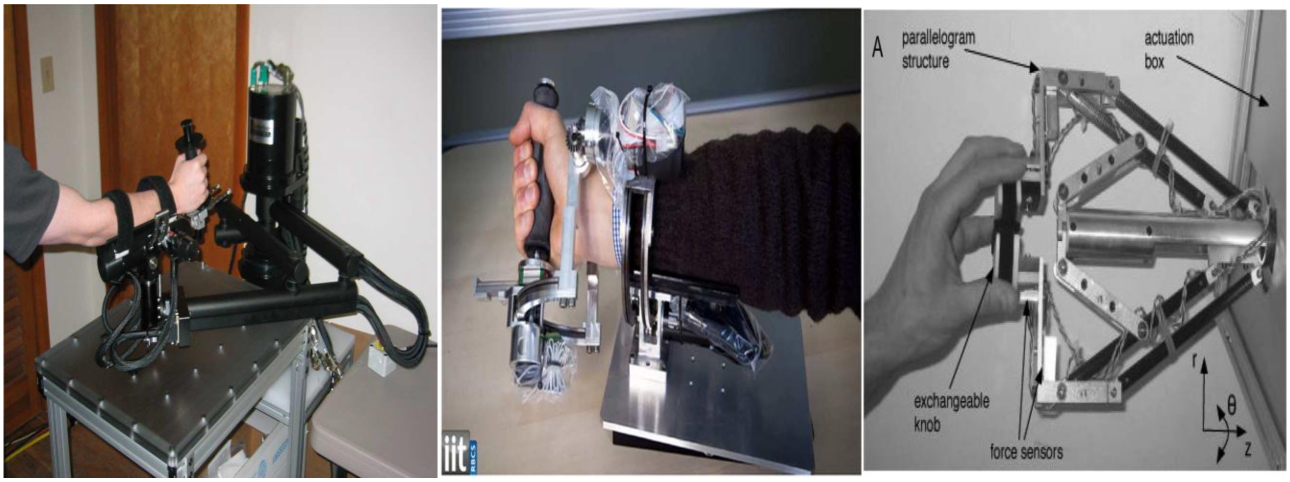


(a) (b) (c)

Fig. 1. End-effector based robotic wrist rehabilitation devices. (a) MIT wrist robot [14]. (b) IIT Genova wrist robot [16]. (c) Haptic Knob [18].

included in this review as they form a separate category of rehabilitation devices. Conference proceedings and peer-reviewed conference papers are excluded from this manuscript. Full upper body robotic rehabilitation systems which do not treat actuation of wrist separately such as a cable driven arm exoskeleton [11] are also not a part of this review. Also, robotic wrist rehabilitation devices utilizing functional electrical stimulation [12] and magnetic stimulation [13] are not a part of this review. Various end-effector based and orthoses-based wrist rehabilitation robot prototypes are presented in Fig. 1 and Fig. 2. The prototypes presented in Fig. 1 and Fig. 2 are selected to give the readers with biomechanics and physiotherapy backgrounds the idea about the difference between orthoses and end-effector type wrist robots. These Figures have been selected based on a suitable combination of the prototypes which are published in top ranked journals of the field, highly cited as well as the most recent ones.

II. Mechanical design

The mechanical design and actuation methods of end-effector based wrist rehabilitation robots as well as wrist rehabilitation robotic orthoses are discussed below (Table 1). Some examples of different types of end-effector based and orthoses-based devices will be described here. The ones that have shown some good outcomes in research and are published in the journal paper format have been included. End-effector based rehabilitation robots are built on the concept of conventional robotic manipulators in which the patients hold the robotic manipulator end-effector which provides required motions to the patient's wrist joint (Fig. 1). Robotic exoskeletons also referred to as robotic orthoses in literature are wearable devices and work in close proximity to the patients' joints (Fig. 2).

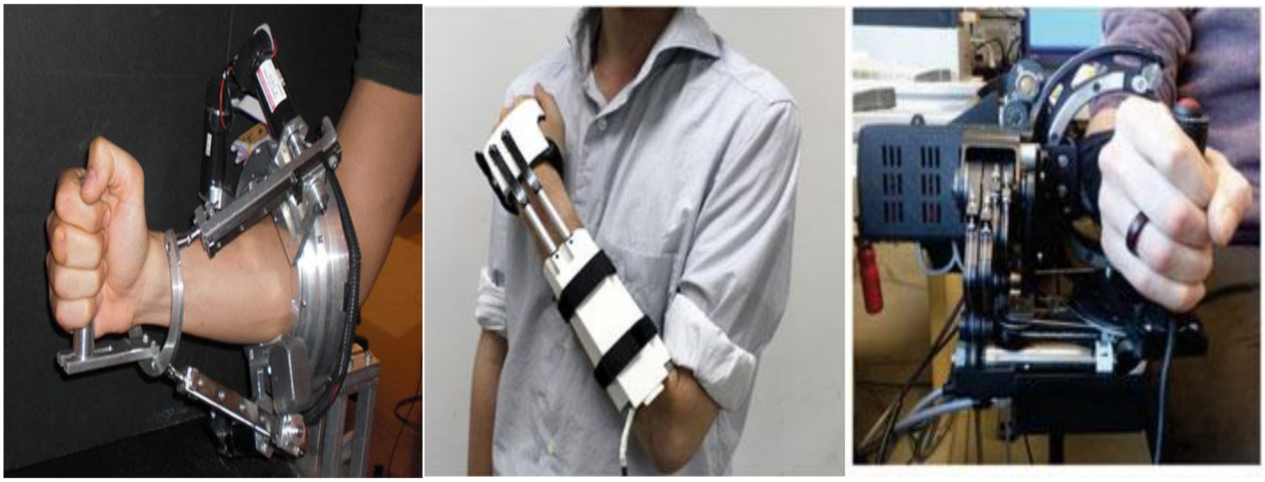
A. End-Effector Based Wrist Rehabilitation Robots

An end-effector based wrist rehabilitation robot has been developed at MIT (Fig. 1a) [14] and works in combination with the MIT's Manus [15]. The wrist rehabilitation robot can provide three actuated Degrees-of-Freedom (DOFs) namely; abduction/adduction; flexion/extension; pronation/supination to the stroke survivors' wrist. These three DOFs are powered by using servo motors. The wrist rehabilitation robot is commercially available by the name of InMotion Wrist Robot [7] (Bionik Laboratories Corp., Watertown, MA, USA).

Another end-effector based wrist rehabilitation robot has been developed at IIT Genova and also provides three DOFs abduction/adduction; flexion/extension; pronation/supination to the stroke survivors' wrist (Fig. 1b) [16]. The authors describe it as a robotic exoskeleton. However, the prototype does not satisfy the design of an exoskeleton/orthosis as its not wearable and is an end-effector robot by its functionality. The robotic system is powered by four brushless DC motors. Two motors are used to allow for abduction/adduction motion and gravity compensation and two other motors are used to power each flexion/extension and pronation/supination.

An end-effector based robot has been design at University Teknologi Malaysia (UTM) which can provide abduction/adduction; flexion/extension; pronation/supination to the stroke survivors' wrist [17]. However, the details of its mechanical design are not provided in literature. An end-effector based robotic Haptic-Knob has been design at National University of Singapore for training the opening/closing of the hand as well as the pronation/supination of the forearm (Fig. 1c) [18, 19]. The Haptic Knob has two DOFs. Parallelogram mechanism, linear bearing as well as belt driven mechanism has been used in combination with DC motors to provide two DOFs to the Haptic Knob. A single DOF end-effector based robotic device has been developed at Free University of Berlin for providing forearm pronation/supination and is powered by DC motor [20].

A robotic device for providing wrist flexion/extension has been developed at University of California, Berkley. The robotic device is powered by a DC motor and provides the single DOF wrist motion when the stroke survivor grasp the end-effector [21]. A single DOF wrist rehabilitation robot (WReD) for providing flexion/extension motion has been



(a) (b) (c)

Fig. 2. Robotic wrist rehabilitation orthoses. (a) RiceWrist [8]. (b) Kyushu University robotic orthosis [32]. (c) WRES [36]

developed at Tongji Zhejiang College, China and is powered by DC motor [22]. A robotic manipulator for providing flexion/extension and abduction/adduction motion to the wrist joint of stroke survivors has been proposed in [23] and is powered by servo motors. A Universal Haptic Drive (UHD) has been developed for wrist rehabilitation [24]. UHD can provide actuation to three DOFs of the wrist joint. It can provide abduction/adduction motions in any configuration whereas the user can select between the flexion/extension and pronation/supination motions depending upon the configuration of use. UHD actuation mechanism works on the basis of Series Elastic Actuation (SEA) [25]. SEA is composed of DC motors working in series with elastic elements such as cable or springs or a combination of both. DC motors are placed on a remote station and the actuation is transferred to the robot joints by using these cables or springs. Same concept of using DC motors in series with elastic springs has been utilized for powering UHD. An end-effector haptic robot omega.7, based on delta-based parallel kinematics has also been reported in literature and commercially available for wrist joint rehabilitation [26]. The omega.7 is powered by servo motors and provide three DOFs to the wrist joint [26].

B. Wrist Rehabilitation Robotic Orthoses/Exoskeletons

A wrist rehabilitation exoskeleton robot has been developed at Rice University which is also called as RiceWrist (Fig. 2a) [8-10]. RiceWrist provides four DOFs to the wrist and forearm. RiceWrist is designed based on the serial-in-parallel mechanism and is composed of three revolute-prismatic-spherical wrist [27]. This mechanism supports the abduction/adduction; flexion/extension; forearm pronation/supination motions. The fourth DOF is the vertical translation of the platform and provides minor alignment of the anatomical wrist axes with the robotic platform. The forearm motion is powered by a frameless brushless DC motor with direct actuation. The wrist platform is powered by utilizing high torque rotary electric motors and capstan drive transmission [9].

A single DOF robotic exoskeleton has also been designed at Seoul National University (SNU) for providing flexion/extension to the wrist joint of stroke survivors [28, 29]. The exoskeleton is powered by a brushless DC motor. A single DOF robotic exoskeleton has been developed at Stanford University for providing forearm pronation/supination and is powered by servo motor [30]. A wrist robotic exoskeleton has been developed at University of Sheffield for providing physical therapy to stroke survivors [31]. The robotic exoskeleton provides flexion/extension to the wrist joint by using a double parallelogram mechanism and electromagnetic actuator.

A two DOF robotic wrist exoskeleton has been developed by researchers at Kyushu University, Japan (Fig. 2b) [32]. The exoskeleton provides flexion/extension and abduction/adduction motions by using spring blade mechanism in combination with linear motors. A two DOF robotic wrist exoskeleton has also been developed at McGill University for providing flexion/extension and abduction/adduction motions to the stroke survivors [33]. A servo motor has been utilized to power each of these DOFs. A modular robotic exoskeleton for upper limb rehabilitation has been designed at Northwestern University, Chicago having a single DOF for providing flexion/extension to wrist joint of stroke survivors [34]. The wrist exoskeleton is powered by a DC motor in conjunction with zero-backlash harmonic gear [34]. A soft robotic orthosis has been developed at Harvard University for wrist rehabilitation of stroke survivors [35]. The robotic orthosis is made of soft textile materials and is powered by a relatively new type of actuators called as Pneumatic Muscle Actuators (PMA). PMA can only provide pulling force and hence are used in pairs to provide a single DOF. The soft robotic orthosis supports the abduction/adduction; flexion/extension and pronation/supination motions.

A robotic wrist exoskeleton (WRES) has recently been proposed in literature (Fig. 2c) [36]. WRES provides three DOFs to the wrist joint for abduction/adduction; flexion/extension and pronation/supination motions. WRES provides actuation to the wrist joint by using DC geared motors. The actuation of these DC motors is transferred to the wrist joint by using capstan-based tendon driven solution. Tendon based transfer of motor actuation falls under the domain of SEA as discussed above and helps in reducing the overall weight of the robotic orthosis. ARMin [37] and its subsequent variants such as ARMin I [38], ARMin II [39] and ARMin III [40] has been developed at ETH Zurich and are commercially available from HOCOMA, Switzerland. ARMin is developed as a six DOF full upper limb exoskeleton and only provides wrist flexion/extension. A servo motor is utilized to power the flexion/extension motion. CHARMin is built for pediatric rehabilitation and also commercially available from HOCOMA, Switzerland [41]. Its design is based on the ARMin design and provides flexion/extension at the wrist joint with the help of servo motor.

C. Actuation Classification of Wrist Rehabilitation Robots

Actuation is an important aspect in the mechanism design and control of wrist rehabilitation robots as they are the main powering elements. The initial versions of end-effector based and orthoses-based wrist rehabilitation robots have been powered by electromagnetic actuators. MIT's robot, IIT Genova robot, Haptic Knob, Free University Berlin robot, University of California Robot, RiceWrist and SNU robot has been powered by electromagnetic actuators (Table I).

The electromagnetic actuators are heavy and have high end-point impedance [42]. In order to design light weight and low end-point impedance wrist rehabilitation robots, different concepts of compliant actuators have been introduced. The most common of these are based on the principle of SEA. UHD and WRES have been designed by using SEA (Table I). Later, the concept of unidirectional force generating actuators such as PMA has also been utilized for the design of compliant wrist rehabilitation robots such as Harvard University Robot (Table I).

III. CONTROL PARADIGMS

The control of wrist rehabilitation robots is an important and emerging area of research. Various control paradigms have been developed for the above-mentioned end-effector and exoskeleton-based wrist rehabilitation robots (Table 1). The purpose of these control paradigms is to guide the patients' limbs on reference trajectories by controlling the robot applied forces and moments. These control paradigms could be divided into two main categories, namely; Trajectory tracking and Assist-as-Needed (AAN) Control.

A. Trajectory Tracking Control

The preliminary versions of robotic wrist rehabilitation orthoses worked on the basis of trajectory tracking control. In trajectory tracking control, the robotic device guides the patients' wrist joint on pre-defined trajectories. These pre-defined trajectories could be obtained from the healthy subjects as well as from the biomechanics literature. The patient remains completely passive in the trajectory tracking control mode and does not offer any of his/her muscular contribution towards the robot assisted rehabilitation. In this manner the robotic device guides the wrist joint of patient on pre-defined trajectories. Trajectory tracking control is also referred to as 'passive training mode' in literature.

A trajectory tracking control paradigm has been utilized for the UTM wrist rehabilitation robot [17]. A proportional-derivative (PD) control law has been used to reduce the trajectory tracking errors and guide the patients' wrist joint on pre-defined trajectories. A similar trajectory tracking control paradigm has also been implemented for the Free University of Berlin robotic device [20]. A trajectory tracking control paradigm based on PD control law has been developed for the University of California, Berkley rehabilitation robot [21]. The trajectory tracking works on the principle of Hand-Object-Hand rule which requires bimanual coordination of both wrist joints [21].

A trajectory tracking control paradigm based on the proportional-integral (PI) control law has been implemented for the McGill University robotic exoskeleton [33]. The desired reference trajectories recommended by the physical therapists have been utilized to guide the patients' limbs on those trajectories by using the PI control law. A trajectory tracking control paradigm based on the fiction and gravity compensation elements has also been implemented for the WRES [36].

B. Assist-as-Needed Control

The trajectory tracking control methods guide the patients' wrist on the pre-defined trajectories without considering the patients' disability level. Also, the patients may feel discomfort as the robotic device do not allow them to move their wrist joints according to their preference. To overcome these limitations of trajectory tracking control several adaptive control paradigms have been developed which can estimate the patients' intent and can modify the robot applied forces to enhance patients' active participation in the rehabilitation process. These control paradigms are generally referred to as AAN control, 'active training mode' or 'patient-cooperative control strategies' in the rehabilitation literature.

The MIT end-effector based wrist rehabilitation robot [14] has incorporated the feature of backdrivability which is one of the most common forms of the AAN control paradigm for rehabilitation robots. Backdrivability is achieved by lowering the endpoint impedance of electromagnetic actuators which power the rehabilitation robot and allows the patients to move the robotic device according to their muscular strength [43, 44]. In other words, backdrivability is used to provide more freedom to the patients to train according to their intent by reducing the resistance offered by the rehabilitation robot.

Impedance control [45] is the most common form of AAN paradigm which has been utilized for providing customized robot assisted rehabilitation. An impedance control scheme has also been implemented for the IIT Genova wrist rehabilitation robot [16]. The impedance control paradigm measures the human-induced joint torque by using force sensors and increases or decreases the robot applied torques based on that. If the human-induced torque is increased the robot applied torque will decrease and vice versa. In this way the patients can actively contribute towards the robotic rehabilitation process. An impedance control paradigm has also been developed for the National University of Singapore Haptic Knob [18, 19].

TABLE I
SUMMARY OF WRIST REHABILITATION ROBOTS

Device Name	DOFs	Actuation Type	Control Method	Feedback Signal	Experimental Evaluation
MIT robot	Three	Servo motors	Impedance control (AAN)	Load cell, encoders	36 Stroke participants
IIT Genova Robot	Three	DC motors	Impedance control (AAN)	Load cell, encoders	9 Stroke participants
UTM Robot	Three	Not Provided	PD Trajectory Tracking	Not Provided	7 Stroke participants
Haptic Knob	Two	DC motors	Impedance control (AAN)	Load cell, encoders, BCI	15 Stroke participants
Free University Berlin Robot	One	DC motor	PD Trajectory Tracking	Load cell, encoders	12 Stroke participants
University of California Robot	One	DC motor	PD Trajectory Tracking	Load cell, encoders	3 Healthy participants
WReD	One	Servo motor	Impedance control (AAN)	Torque sensor, encoder	1 Healthy participant
UHD	Three	SEA	Impedance control (AAN)	Linear potentiometer	1 Stroke participant
RiceWrist	Three	DC motors	MPC control (AAN)	Load cell, encoders	5 Healthy participants
SNU Robot	One	DC motor	Not Provided	Torque sensor	20 Stroke participants
Kyushu University Robot	Two	Linear motors	Not Provided	Load cell, camera	1 Healthy participant
Sheffield University Robot	One	DC motor	Not Provided	Rotary potentiometer	23 Stroke participants
McGill University Robot	Two	Servo motors	PI Trajectory Tracking	Load cell, potentiometer	1 Healthy participant
Northwestern University Robot	One	DC motor	Impedance control (AAN)	Load cell, potentiometer	3 Stroke participants
Harvard University Robot	Three	PMA	Not Provided	Not Provided	1 Healthy participant
WRES	Three	SEA	Trajectory Tracking	Encoders	1 Healthy participant
ARMin	One	Servo motors	Impedance control (AAN)	Load cell, potentiometer	4 Stroke participants
Omega.7	Three	Servo motor	Virtual Reality (AAN)	Not Provided	7 Stroke and 3 TBI participants

Abbreviations: UHD, Universal Haptic Drive; SEA, Series Elastic Actuators; PMA, Pneumatic Muscle Actuators; AAN, Assist-as-Needed; MPC, Model Predictive Control; PD, Proportional Derivative; PI, Proportional Integral; TBI, Traumatic Brain Injury; BCI, Brain Computer Interface; WReD, Wrist Rehabilitation Device.

Impedance control works on the basis of friction compensation for the opening/closing mechanism. A feedforward compensation element has also been incorporated in the impedance control scheme which helps in providing assistive or resistive robotic assistance depending on the patients' intent and active level of participation.

Admittance control is another control paradigm which has been proposed in literature for providing AAN control of rehabilitation robots [46]. Admittance control provides better stability at higher impedances as compared to impedance control. Readers are referred to the work of Riener *et al*. for more details related to admittance control [46]. An AAN control paradigm based on admittance control scheme has been implemented for WReD rehabilitation robot [22, 47]. A static torque sensor has been utilized to measure the human-robot interaction moment and the robot applied force is increased or decreased depending on the level of human-robot interaction moment.

A hybrid impedance control scheme [48] for providing AAN robotic wrist rehabilitation has been implemented in [23]. In the hybrid impedance control method, the mechanical impedance of the robot is adjusted while the robot is still doing trajectory or force tracking. The hybrid impedance control implemented for wrist rehabilitation robot has incorporated both force based and position based impedance control [23]. An impedance control scheme has been implemented for the UHD [24]. The concept of virtual impedance has been utilized for UHD. Virtual impedance selection is performed to quantify the magnitude of robot applied force to the patients' wrist joint. Virtual impedance is varied among two boundaries; a highest-level impedance and a lowest level impedance. The highest-level impedance is ideally infinite and lowest level impedance is ideally zero.

An AAN control paradigm based on the model-predictive control (MPC) law [49] has been designed and implemented for RiceWrist [8-10]. The AAN controller modifies the magnitude of allowable trajectory tracking error based on patients' performance. A feedforward element in the AAN control scheme has been incorporated to estimate the force contributed by patients towards the robotic rehabilitation process. Based on that force contribution, the allowable limits of trajectory tracking errors are modified. An AAN training scheme based on virtual reality (VR) has been developed for the omega.7 robot [26]. Various virtual haptic-guided tasks have been designed to assess various wrist motor functions [26].

Two different control modes have been implemented for the

Northwestern University's modular robotic exoskeleton [34]. The first mode is the passive one in which the patients are completely passive, and the robot is driving their wrist joint on predefined trajectories by utilizing a trajectory tracking control paradigm. The second control mode is active in which the patient is driving the robot by utilizing internal model-based impedance control. Internal model based impedance control is a modified form of impedance control and was developed to overcome problem of tradeoff between impedance accuracy and robustness against modelling error [50]. A traditional impedance control scheme has also been implemented for ARMin [37], ARMin I [38], ARMin II [39] and ARMin III [40].

The control paradigms for Seoul National University robotic exoskeleton [28, 29], Stanford University robotic exoskeleton [30], University of Sheffield robotic exoskeleton [31], Kyushu University robotic exoskeleton [32] and Harvard University soft robotic orthosis [35] are not provided in sufficient detail in literature.

C. Feedback Signals

Feedback signals are the most important elements in the design of above-mentioned control paradigms for the wrist rehabilitation robots. These signals are also critical in terms of quantitatively evaluating the progress and recovery of the patients. Different sensors and transducers have been employed in the design of wrist rehabilitation robots for providing these feedback signals (Table I). MIT's wrist rehabilitation robot has utilized load cells and rotary encoders for obtaining interaction force and kinematic feedback signals, respectively [14]. Similarly, IIT Genova robot has also used load cells and rotary encoders [16]. A load cell has been used for force feedback in the design of Haptic Knob and encoders have been utilized for position feedback signal [18, 19]. Load cell and encoders embedded in the DC motor drives of Free University Berlin robot were used to provide force and position feedback, respectively [20]. University of California robot has utilized potentiometers for trajectory tracking control and load cell for the force feedback signal [21]. WReD has used a static torque sensor for static force feedback and a magnetic rotary encoder for position feedback [22].

UHD has utilized linear potentiometers for the implementation of its impedance control scheme [24]. RiceWrist has used optical encoders for position feedback and load cells for measuring the human-robot interactions for its AAN control paradigm [9]. SNU robot has also utilized torque sensors for measuring human-robot interaction [28, 29]. Kyushu University robot has used a load cell for human-robot interaction torque feedback and a camera based motion analysis system for determining the position online [32]. Integrated measurement unit based on potentiometer has been designed for University of Sheffield robot to measure the wrist kinematics [31]. McGill University robot [33] and Northwestern University robot [34] have also used potentiometer and force sensor for kinematic and human-robot interaction torque measurement, respectively. Optical encoders have been used in the design of WRES for recording and controlling the kinematic parameters [36]. ARMin has utilized optical incremental potentiometers and load cells for position and torque measurement, respectively [37].

Recently, there has been an increasing trend for using the biomedical signals such as EMG and EEG as feedback signals for the rehabilitation robots. However, few studies utilizing these biomedical feedback signals have been reported in literature. Recently, a low cost EEG sensor has been used to provide feedback signal for the control of a two DOF wrist rehabilitation robot which can provide flexion/extension and radial/ulnar deviation [51]. A brain computer interface based control method has also been reported in literature for Haptic Knob [52]. EEG and EMG signals have been utilized as feedback signals for the control of haptic knob. Biofeedback signal based on the EMG has also been utilized for a three DOF wrist rehabilitation robot [53]. Assessment if wrist muscle activations has been performed which indicated that the EMG signals could be incorporated in the low-dimensional control of wrist rehabilitation robots [53].

IV. Experimental Evaluations

The experimental evaluation of these robotic orthoses with healthy and neurologically impaired subjects is gaining importance in the rehabilitation engineering and physical therapy community (Table I and II). Preliminary experimental evaluations have been conducted to validate the mechanical design and control paradigms with healthy subjects and to ensure the safety of these robotic devices. After completion of evaluations with healthy subjects these robotic devices have been evaluated with neurologically impaired subjects to establish therapeutic efficacy. The experimental evaluations are divided in two categories. First papers which use these robotic devices to evaluate motor function outcomes are reviewed. Second, papers aimed at validating the design and control paradigms of wrist robots fall are presented.

A. Evaluation of Motor Function Outcomes

Reported evaluations are variable in terms of research quality, so to assist awareness of the relative quality of research design of the papers presented, the level of evidence has been rated according to the National Health and Medical Research Council (NHMRC) Evidence hierarchy [54] and displayed in Table II. Investigations of the effectiveness of these devices is at an early stage, with most papers rated at level IV (case series with pre/post-test outcomes) apart from three devices with level III evidence (pseudorandomized controlled trials). MIT's wrist rehabilitation robot along with its control paradigm has been evaluated with thirty-six stroke survivors having severe to very severe chronic impairment [14]. A twelve-week program of robot assisted wrist therapy was delivered spanning over thirty-six sessions. The wrist robot assisted therapy showed a motor function improvement of 10% in terms of Fugl-Meyer (FM) score for these stroke survivors. MIT's wrist robot has also been evaluated with twenty subacute and twenty chronic stroke participants [7]. Five thirty-minute training sessions per week were conducted for each participant for six weeks. Improvements in Fugl-Meyer score of subacute participants were recorded and were higher as compared to the chronic participants. Also, improvements in the movement velocity, movement smoothness and movement quality of subacute group were recorded [7].

TABLE II
NHMRC LEVEL OF EVIDENCE

Device Name	Evidence Level
MIT robot	Level III-2
IIT Genova Robot	Level IV
UTM Robot	Level IV
Haptic Knob	Level IV
Free University Berlin Robot	Level IV
University of California Robot	Level IV
ARMin	Level IV, III-2

Level I- systematic review of level II studies; Level II- Randomised controlled trials; Level III-1- Pseudorandomized controlled trial; Level III-2- Comparative study with concurrent controls; Level III-3- Comparative study without concurrent controls; Level IV- Case series with post-test or pre-test/post-test outcomes.

IIT Genova wrist robot along with its control paradigm has been evaluated with nine stroke survivors suffering from mild to severe impairment [16]. Ten therapy sessions of one-hour duration were conducted for each stroke survivor over five weeks. Improvements in the range of motion of all DOFs, and motor function assessed by the Fugl-Meyer score and WOLF motor function test were found for all stroke survivors [16]. A three month follow up assessment has also been performed for the same nine stroke survivors and has provided evidence of long lasting improvements [16].

The University Teknologi Malaysia's (UTM) wrist rehabilitation robot has been evaluated with seven participants suffering from chronic and sub-acute stroke [17]. Thirty sessions with a duration of thirty-minute each session was performed for each participant. The results demonstrated improvements in the motor function of all stroke participants assessed by the Fugl-Meyer score. Improvements in the wrist flexion/extension and pronation/supination ranges of motion were noted for all participants after robot assisted therapy. The National University of Singapore robotic Haptic-Knob and control paradigm has been evaluated with stroke participants in two different studies [18, 19]. In the preliminary study, the Haptic-Knob has been evaluated with three participants with chronic stroke. These three participants had some functional impairment of their right hand which prohibited them from performing ADL [18]. The stroke participants were instructed to turn the knob and a comparison of the same task has been carried out between stroke and healthy participants. The comparison demonstrated that the movement of stroke participants was slower and the applied forces to the knob were smaller as compared to healthy participants [18].

Quantitative evaluation of these robotic devices is critical for establishing therapeutic efficacy [55]. The quantitative evaluation of robot assisted upper limb motor function recovery based on metrices of kinematics [56] and dynamics [57] have been provided in literature. However, limited studies regarding the quantitative evaluations of the wrist rehabilitation robots have been reported. A quantitative evaluation of upper limb motor control with MIT's wrist rehabilitation robot has been performed with stroke subjects [55]. Double functions based on FM score, motor power and a core set of kinematic/dynamic as well as other motion planning indices have been evaluated during robot assisted wrist rehabilitation [55]. Significant improvements in the kinematic motor performance have been observed [55]. Omega.7 has been evaluated with seven stroke and three traumatic Brain Injury (TBI) subjects. A quantitative performance based on the measures of completion time, contact force and motion trajectory has also been reported in literature for Omega.7. The quantitative assessment has provided encouraging results for the use of Omega.7 rehabilitation robot [26]. Quantitative assessments of IIT Genova [16] and UTM's wrist [17] rehabilitation robots have been carried out with stroke patients in terms of kinematic parameters, resulting in significant improvements of motor function. Quantitative evaluation of Haptic knob was carried out with fifteen chronic stroke participants [19]. Six weeks practice of three-hour sessions per week occurred. Improvement in the hand motor function assessed by the FM score was recorded for the stroke participants. Also, improvements in the hand function was observed for these participants as measured by factors such as motor assessment scale, grip force and reduced muscle spasticity [19].

Different studies related to the quantitative evaluation of RiceWrist and its control paradigm has been reported in literature [8-10]. RiceWrist has also been evaluated with one neurologically impaired participant [27]. Movement smoothness and motor impairment after robot assisted therapy were evaluated by using parameters such as muscle strength, motor function, grips and pinch forces. Improvements in the movement smoothness and motor impairment level was recorded post training with RiceWrist [27]. ARMin has been extensively evaluated with the hemiplegic participants [37]. Clinical assessments of ARMin have also been performed with stroke participants and have provided encouraging outcomes in terms of range of motion and human-robot interaction measurements [58, 59]. ARMin II has been evaluated with four chronic stroke participants and improvements in the motor function of three stroke participants were recorded. The improvements in motor function were maintained by these participants in a six-month follow up evaluation [39]. CHARMin has been evaluated with five children suffering from stroke and cerebral palsy and have provided encouraging results [41].

Free University of Berlin robotic device has been quantitatively evaluated with twelve chronic stroke participants [20]. A fifteen-minute therapy session every day was provided to each participant for three weeks. The outcomes in terms of spasticity and motor function were assessed by using the Modified Ashworth Scale (MAS) score and the Rivermead

Motor Assessment (RMA). Improvements occurred as the MAS score decreased, and RMA score increased for all participants after three weeks of robot assisted therapy.

B. Validation of Robot Design and Control

University of California, Berkley robotic device has been evaluated with three healthy participants [21]. The healthy participants first performed the squeezing task according to point a computer display cursor onto a target. Later, the left hand of all subjects was made ischemic and the same squeezing task was performed. The desired squeezing force was achieved with the help of robotic device despite the hand being made ischemic [21]. WReD and its control paradigm has been evaluated with one healthy participant [22]. The robotic device provided satisfactory trajectory tracking results as well as the reduction in robot applied force with an increase in human participants' activity level [22].

Kyushu University robotic wrist exoskeleton has been evaluated with one healthy participant [32]. The evaluations have demonstrated that the robotic exoskeleton can provide the desired range of motion and forces to carry out the physical rehabilitation. McGill University robotic wrist exoskeleton has also been evaluated with one healthy participant for mechanical design validation [33]. It has been reported that the robotic exoskeleton can provide the intended range of motion as well as desirable robot torque.

Northwestern University robotic exoskeleton and its control paradigm has been evaluated with three stroke participants [34]. Several kinematic and kinetic paraments during the robot assisted training has been recorded to evaluate the efficacy of the device. Few parameters which were recorded include passive and active changes of the range of motion as well as the muscle stiffnesses. The evaluation has provided encouraging evidence for the utility of robotic exoskeleton for physical therapy [34]. Harvard University soft robotic orthosis has been evaluated with one healthy participant [35]. The evaluation was performed to validate the design and actuation capability in terms of in terms of range of motion and robot applied torque, respectively. The experimental evaluation with healthy participant has provided intended results. WRES mechanical design and trajectory tracking control has been evaluated with one healthy participant and has provided satisfactory results [36].

The robotic manipulator and its control paradigm proposed in [23] has been evaluated with four participants suffering from peripheral nerve lacerations. Isometric joint force has been measured and assessed for all participants undergoing robot assisted therapy. The increase in flexion/extension isometric muscle force was recorded for all participants [23]. UHD and its control paradigm has been evaluated with one chronic stroke participant [24]. Six training sessions have been performed with the participant spanning over six consecutive days. The objective of the evaluation was to validate that the achievable impedance range of the robotic device is enough for adequately assisting the participant to perform movement tracking tasks. The results showed that only the tracking task in horizontal plane is achievable for UHD assisted movement. This presents a limitation of the robotic device [24].

RiceWrist and its AAN controller has been evaluated with five healthy participants in [8]. The AAN controller has decreased with robot applied force when the healthy participants have increased their voluntary forces. This demonstrates the efficacy of the AAN control scheme with healthy participants. RiceWrist has also been evaluated with nine healthy participants to study different movement patterns of wrist joint [10]. Stanford University robotic exoskeleton has been evaluated with twenty one chronic stroke participants [30]. Improvements in the strength and motor function has been recorded post robot assisted therapy with the stroke participants [30]. University of Sheffield robotic exoskeleton has been evaluated with twenty three chronic stroke patients for six weeks [31]. However, no performance outcome measures have been reported in literature [31].

C. Biomechanical Assessment

An important advantage of these rehabilitation robots apart from the physical therapy is their utility in conducting biomechanical assessments of wrist joint. SNU robotic exoskeleton has been evaluated with twenty stroke participants with spastic upper limb [28, 29]. The purpose of the study with stroke participants was to evaluate the biomechanical reactions of the robotic exoskeleton to spastic upper limb and provide the reference robot applied torque to such spastic upper limb. This study has provided the desired values of robot applied torque to spastic wrists. An end-effector based wrist rehabilitation robot has been used to conduct the biomechanical assessment in the form of wrist passive [60] and active ranges of motion for wrist flexion/extension and radial/ulnar deviation [47]. These biomechanical assessments were performed with eleven healthy subjects. Similarly, the RiceWrist robot has been utilized for assessing wrist movement [10]. Kinematic and dynamic parameters have been studied with three healthy subjects and design guidelines have been established for robotic orthoses utility as kinematic assessment tools [10].

MIT robot has been utilized to study the passive wrist joint stiffness [61]. The effect of handedness and gender on wrist passive stiffness has been reported [61]. A three DOF wrist rehabilitation robot has also been utilized to study the effect of robot mediated movements on muscle fatigue and has proven to be an objective, fast and reliable method for muscle fatigue assessment [62]. The reliability of these robot based biomechanical assessments have also been an important research consideration as very few reliability tests have been reported in literature. The only major study dealing with the reliability of these assessments have been reported for the wrist passive [60] and active ranges of motion [47] where a high reliability has been recorded. This demonstrates that these robots based biomechanical assessments provide an alternative and reliable automated tool for the study of wrist kinematic and kinetic parameters as compared to the existing biomechanics methods.

V. DISCUSSION AND FUTURE DIRECTIONS

Various end-effector based and wearable robotic orthoses for wrist rehabilitation of neurologically impaired subjects have been reported in literature. The preliminary forms of end-effector based wrist rehabilitation robots were based on the modified versions of industrial robotic manipulators and were powered by electromagnetic actuators such as DC and servo motors. These end-effector designs present two drawbacks. Firstly, the patients are instructed to hold the robotic end-effector and the forces were applied to the forearm. The accuracy of application of these forces at the desired position of the wrist joint is a significant challenge. The accuracy of applied forces and moments at the effected joint is a major theme of research in the field of rehabilitation robotics. Secondly, all these robotic end-effector based rehabilitation robots were powered by inherently stiff electromagnetic actuators. The use of these stiff actuators has raised issues in the design domain of comfort and human-robot interaction [42]. Several control algorithms have been developed to make these electromagnetic actuator powered rehabilitation robots compliant and backdrivable. However, this has added an extra layer to control complexity in the design of control paradigms.

To overcome the mechanical design limitation of end-effector based wrist rehabilitation robots, several robotic exoskeletons (*i.e.* orthoses) have been developed. However, most of these robotic orthoses only provide a single or two DOFs at the wrist joint, whereas the anatomical wrist joint has 3 DOFs. These robotic orthoses are also powered by electromagnetic actuators with the exception of Harvard University soft robotic orthosis. Several control algorithms have been utilized to make these robotic orthoses compliant. These robotic orthoses are also made of metal or plastic composite frame rigid structures and the actuators are embedded in the design to provide motions to the wrist joint. The application of robot applied moments at the wrist joint is important as there are some misalignments between the robotic orthosis joints and the anatomical joints of the human user. The robotic orthosis joints at which the actuators apply the forces are often misaligned during the operational mode of the robot [63]. This misalignment presents serious issues as it may further damage the wrist joint of patients with the inexact point of application of robot moments. Several methods have been proposed in literature to achieve joint alignment for robotic rehabilitation orthoses with an anatomical elbow joint [64, 65]. However, no such effort has been reported in literature for wrist rehabilitation orthoses as the wrist is anatomically a more complicated joint compared to elbow. Therefore, there is a strong need to design and evaluate robotic wrist rehabilitation orthoses which can provide better joint alignment with the anatomical wrist.

In order to overcome the issues arising from the rigid frame based robotic orthoses, there is a need to develop soft robotic orthoses which can increase the comfort of these devices as well as will make them safer for interacting in close proximity with patients. Also, these soft or inherently compliant robotic orthoses will solve the issue of joint misalignment to a great extent as these soft orthoses will have greater bending capability with the anatomical joints. This will increase the ease of wearability as well. Harvard University soft robotic orthosis is not based on the rigid frame structure and flexible textile-based linkages are used to transit the actuators forces to the wrist joint. However, detailed description regarding the design, control and experimental evaluations of the soft robotic orthosis are not reported in literature.

Actuation is also a crucial component in the development of these robotic wrist rehabilitation devices and the selection of appropriate actuation systems plays a critical role in the proper functionality of these devices. The majority of end-effector based, and orthoses-based wrist rehabilitation robots are powered by inherently stiff electromagnetic actuators. UHD uses the concept of SEA which helps in providing relatively more compliant actuation as compared to other end-effector based devices. Similarly, Harvard University soft robotic orthosis is powered by inherently compliant PMA. However, the PMA can only be used in pairs to provide actuation to a single DOF. This results in the redundant actuation of the robotic rehabilitation orthoses which causes issues in the design and control. This demonstrates a strong need for development of new actuation methods for the rehabilitation robots which can provide compliant and safe human-robot interaction. Many such compliant actuators have been proposed in literature [66, 67] but majority of them are still at development stages and can only offer peak forces which are much less in magnitude than the required forces to actuate the wrist rehabilitation robots.

Several control paradigms for these robotic end-effector based and orthoses-based wrist rehabilitation devices have been reported in literature. Most of these control paradigms have been designed on the basis of AAN in which the patients' active participation in the rehabilitation process is monitored and the robot applied forces are adjusted accordingly. However, these AAN control paradigms are still lacking in two major areas. Firstly, there is a lack of use of biomechanical wrist models in the development of AAN control paradigms. Mostly, the anatomical wrist joint models have been ignored and the electromechanical sensors embedded in the robotic wrist devices are used to estimate the patients' active participation. These estimates are not enough to present the true biomechanical nature of human wrist joint. Recently, a model-free, data-driven control theory has been proposed in literature [68] which can potentially solve this issue with the model-based AAN control. This control theory has been implemented for a parallel ankle rehabilitation robot [69]. The similar model-free methods could be adapted for wrist the wrist rehabilitation robots. Secondly, the AAN control algorithms for wrist robots guide the patients' wrist joint on pre-defined trajectories. It is important to mention here that the motion of each patient's wrist joint is different and varies within the several rehabilitation stages for each patient. Several reference trajectory generation algorithms have been designed and implemented for the lower limb rehabilitation robots [70, 71]. However, no significant work has been reported in literature for the wrist rehabilitation robots. Therefore, there is a strong need to develop appropriate biomechanical wrist models which could be adapted for designing the AAN control paradigms. Further, there is a significant need for the development of reference trajectory generation and adaptation methods which could be utilized for the AAN control of wrist rehabilitation robots.

The feedback signals for the AAN control paradigms are crucial for estimating the human-robot interaction. The accuracy of this interaction measurement will aid in providing reliable and objective AAN robot assisted wrist rehabilitation. Majority of these interaction estimation methods are based on the use of force sensors/load cells and the position measurement encoders/potentiometers [72]. Recently, there has been an increasing trend of developing new EMG and EEG based biofeedback signals for designing the AAN control strategies. However, few methods based on biofeedback signals have been reported in literature for wrist rehabilitation robots. The comparison of conventional human-robot interaction estimation methods based on force and position sensors with the biofeedback signals based on EMG and EEG will help in standardizing an effective and objective feedback mechanism for the development of AAN control paradigm of wrist rehabilitation robots.

Majority of the end-effector based and orthoses-based wrist rehabilitation robots with accompanying control paradigms have been evaluated with neurologically impaired patients and have shown promising outcomes. Quantitative evaluations of the wrist rehabilitation robots and their AAN control paradigms have also been performed with the neurologically impaired patients. This is an encouraging development in the field of robot assisted wrist rehabilitation. However, extensive randomized clinical trials need to be performed which can investigate the therapeutic efficacy of these robotic devices. Biomedical signals have also been utilized in the design of AAN control paradigms though the quantitative evaluations of these AAN control paradigms have not been extensively reported in literature. Quantitative evaluations of these biomedical signal based AAN control schemes and the conventional force/position sensor-based schemes will aid in establishing the better practices in the domain of feedback signal acquisitions and processing for robot assisted rehabilitation.

These rehabilitation robots have also been increasingly utilized for the biomechanical assessments of wrist joint [28, 29]. These robots based biomechanical assessments provide an alternative and reliable automated tool for the study of wrist kinematic and kinetic parameters as compared to the existing biomechanics methods. In addition to that, these wrist rehabilitation robots could also be used to study the neuromechanical control of human movement which is a rapidly evolving field of research. One wrist rehabilitation robot has been used to perform such a study [34] and has provided encouraging outcomes. However, further biomechanical studies should be conducted to establish the quantitative and qualitative reliability of these robot-based assessment methods. Also, there is a strong need to develop the standardized methods for conducting these biomechanical assessments. These standardized methods will help in doing the comparison of assessments for different robotic prototypes. Furthermore, the misalignment of these wrist rehabilitation robots with the anatomical joint hinders their capability to conduct reliable biomechanical assessments.

In summary, significant advancements have been reported in literature in the field of robot assisted wrist rehabilitation. Various mechanical designs of end-effector based, and orthoses-based wrist rehabilitation robots have been reported in the literature along with their AAN control paradigms. Several experimental evaluations with neurologically impaired patients have also been conducted with these wrist rehabilitation robots and have provided promising results. There is a need to further develop robotic wrist rehabilitation design solutions which can provide compliant human-robot interaction as well as better alignment of robotic orthosis joints with anatomical wrist. Actuation methods is another area where significant research could be performed to develop better solution in the context of compliant actuation. Better biomechanical models of the wrist joint as well as better methods of generating and adapting reference trajectories must be developed to provide more objective AAN robot assisted wrist rehabilitation.

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