



Review

Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects

Ho Shing Lo*, Sheng Quan Xie*

Department of Mechanical Engineering, The University of Auckland, 20 Symonds Street, Auckland 1010, New Zealand

ARTICLE INFO

Article history:

Received 1 April 2011

Received in revised form 9 October 2011

Accepted 11 October 2011

Keywords:

Exoskeleton

Upper limb

Robotic therapy

Physiotherapy

Stroke rehabilitation

ABSTRACT

Current health services are struggling to provide optimal rehabilitation therapy to victims of stroke. This has motivated researchers to explore the use of robotic devices to provide rehabilitation therapy for strokepatients. This paper reviews the recent progress of upper limb exoskeleton robots for rehabilitation treatment of patients with neuromuscular disorders. Firstly, a brief introduction to rehabilitation robots will be given along with examples of existing commercial devices. The advancements in upper limb exoskeleton technology and the fundamental challenges in developing these devices are described. Potential areas for future research are discussed.

© 2011 IPEM. Published by Elsevier Ltd. All rights reserved.

Contents

1. Introduction	261
2. Rehabilitation robots for the upper limb	262
3. Advancements in upper limb rehabilitation exoskeletons	262
3.1. Exoskeleton joints	262
3.1.1. The mechanical singularity problem	264
3.1.2. Use of redundant DOF	264
3.2. Human–robot interface (HRI)	264
3.3. Actuation	264
3.4. Modelling for control	265
3.5. Exoskeleton control	265
3.5.1. Adaptive control	265
4. Discussion	266
Conflict of interest	266
Acknowledgement	266
References	267

1. Introduction

Stroke is a major cause of adult disability [1]. Stroke is caused by an interruption of blood flow to the brain resulting in damage to brain cells and can be fatal. The survivors of stroke can experience paralysis or loss of physical strength on one side of the body (hemiparesis) as well as memory problems making it difficult to

perform activities of daily living (ADL). Rehabilitation is the main treatment to these disabilities, a process which allows the stroke patient to relearn the best possible use of their limbs and regain independence.

In New Zealand, an estimated 6000 stroke cases occur every year with approximately two thirds of these cases being non-fatal. The Stroke Foundation of New Zealand estimates that the number of stroke survivors in New Zealand has reached 45,000 in 2011 [2]. In addition, as the population of the baby boom generation continues to age and life expectancy continues to improve, the number of elderly in the population is expected to increase in the next few

* Corresponding authors. Tel.: +64 9 3737599x88143; fax: +64 9 3737479.

E-mail addresses: hlo015@aucklanduni.ac.nz (H.S. Lo),
s.xie@auckland.ac.nz (S.Q. Xie).

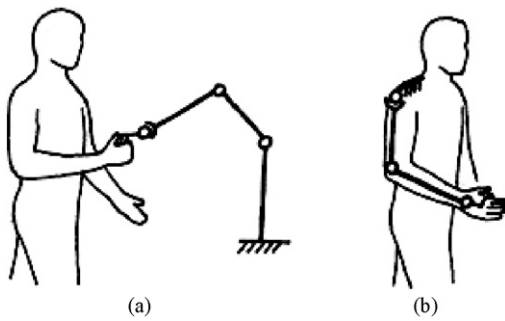


Fig. 1. (a) End-effector robot. (b) Exoskeleton robot. Artwork by Massimo Bergamasco.

Reproduced from [17] with permission.

decades [3]. As a result, stroke cases can be expected to increase as well.

Rehabilitation therapy can continue throughout most of the stroke patients' life, hence can be labourintensive and costly. There are a number of factors which has been found to contribute to faster motor recovery, all of which has not been taken full advantage of due to the lack of rehabilitation services [1]. It has been known that therapy is most effective if performed soon after stroke [4], but this is not always available. In addition, studies have found that intensive therapy and task-based exercises contribute significantly to motor recovery [5]. Physiotherapy for stroke survivors after completing acute stroke rehabilitation showed continued improvement, suggesting that recovery can continue for many years after stroke. As the population of stroke patients continues to grow, providing adequate rehabilitation treatment to patients can be expected to become more and more difficult given its labour intensive nature. Exoskeleton robots have the potential to meet this growing demand which conventional manual therapy is struggling to cope with. These robots are designed to be worn by the patient, having a similar kinematic structure to the human limb.

Compared to manual therapy, exoskeletons have the potential to provide intensive rehabilitation consistently for a longer duration [6] and irrespective of the skills and fatigue level of the therapist. Exoskeletons may be able to treat the patient without the presence of the therapist, enabling more frequent treatment and potentially reducing costs. In addition, it is possible for an exoskeleton to accurately measure quantitative data to evaluate the patient's condition. The use of specially designed virtual games with the exoskeleton can provide a more entertaining therapy experience, promoting the patient to put in their own effort into the exercises [7].

This paper reviews the recent progress of upper limb exoskeleton robots for rehabilitation treatment of patients with neuromuscular disorders. The literature search was done mainly in the Scopus database. Firstly, a brief introduction to rehabilitation robots will be given along with examples of existing commercial devices. The advancements in upper limb exoskeleton technology and the fundamental challenges in developing these devices are described. Potential areas for future research are discussed.

2. Rehabilitation robots for the upper limb

Early research on robotic therapy for the upper limb were based on end-effector robots. End-effector robots hold the patient's hand or forearm at one point and generate forces at the interface (Fig. 1a). The joints of end-effector robots do not match with that of the human limb. This type of robot is simpler, easier to fabricate and can be easily adjusted to fit different patient arm lengths. However, determining the posture of the upper limb can be difficult with only

one interface, especially if the interface is at the patient's hand. Controlling the torque at specific upper limb joints is also not possible, resulting in uncontrolled load transfer between upper limb joints. As a consequence, generating isolated movement at a single upper limb joint is difficult since movement of the end-effector can cause a combination of movements at the wrist, elbow and shoulder joints. In addition, the range of motion that end-effector robots can generate for the upper limb tends to be limited therefore only a limited set of rehabilitation exercises can be produced by these robots. Examples of end-effector rehabilitation robots include the MIT-MANUS [8,9], the MIME [10] and the GENTLE/s [11]. Extensive clinical testing has been done on these devices to evaluate their effectiveness as rehabilitative devices [12–16]. The results indicate reduced motor impairment of the upper limb for patients who received robotic therapy. The positive results justify research on the more sophisticated exoskeleton robots as rehabilitation devices.

Recently, robotic therapy research has shifted towards exoskeleton robots. Exoskeletons have a structure which resembles the human upper limb, having robot joint axes that match the upper limb joint axes (Fig. 1b). Exoskeletons are designed to operate side by side with the human upper limb, and therefore can be attached to the upper limb at multiple locations. Although this can make it more difficult for the robot to adapt to different arm lengths, multiple interfaces may allow the exoskeleton to fully determine the upper limb posture and controlled torques to be applied to each joint separately. It may be possible for exoskeletons to target specific muscles for training by generating a calculated combination of torques at certain joints. In addition, a larger range of motion may be possible compared to end-effector robots which can enable a wider variety of movements to be used in rehabilitation exercises.

There are a number of commercially available rehabilitation devices for the upper limb. One of the more sophisticated rehabilitation devices available is the Armeo products (Hocoma AG, Switzerland). These include the 7 DOF ArmeoPower active exoskeleton, ArmeoSpring passive exoskeleton and ArmeoBoom sling suspension system. The ArmeoPower is based on the ARMin III exoskeleton [18] and will be available at the end of 2011 once clinical trials with the ARMin III are complete. Examples of other commercial devices include the mPower arm brace (Myomo Inc., Cambridge, MA), a 1 DOF portable arm brace which uses electromyogram (EMG) signals measured from the bicep and tricep muscles to generate assistive torques for elbow flexion/extension, and the Hand Mentor (Kinetic Muscles Inc., Tempe AZ), a 1 DOF wearable device for the rehabilitation of the wrist and fingers which provides force, position and EMG feedback and is actuated by an air muscle. The Robot Suit HAL-5 (CYBERDYNE Inc., Japan) is a full body exoskeleton for the disabled. The suit uses measured EMG signals from the user to generate assistive torques. Currently, HAL-5 is only available in Japan under a rental contract. Examples of commercial end-effector rehabilitation robots include the InMotion robots (Interactive Motion Technologies Inc., Boston, MA), Biodex System 4 dynamometer (Biodex Medical Systems Inc., New York), HUMAN NORM (SCMi, Stoughton, MA), and CON-TRES MJ (CMV AG, Switzerland).

3. Advancements in upper limb rehabilitation exoskeletons

3.1. Exoskeleton joints

Operating alongside the human arm, exoskeletons need to be able to produce similar movements to those of the upper limb. The upper limb effectively has a total of 9 DOF excluding the finger joints [19]. The glenohumeral joint at the shoulder complex is a ball-and-socket joint which enables the humerus to rotate about the glenohumeral head in 3 DOF. These movements are commonly referred to as shoulder flexion/extension, abduction/adduction

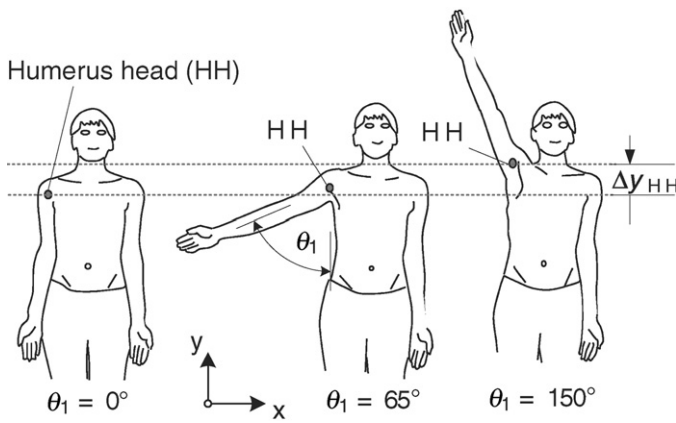


Fig. 2. Elevation during abduction of the shoulder.

Adapted from [18] with permission.

and medial/lateral rotation. The sternoclavicular joint has 2 DOF, commonly known as shoulder elevation/depression and retraction/protraction, which moves the glenohumeral head. Thus the shoulder has a total of 5 DOF. An interesting phenomenon of the shoulder is that abduction of the upper arm above the horizontal plane will occur simultaneously with shoulder elevation (Fig. 2) [20]. The elbow complex is capable of 2 DOF, these are elbow flexion/extension and forearm pronation/supination. The wrist joint has 2 DOF, wrist flexion/extension and radial/ulnar deviation. The axes of rotation of both DOF of the wrist pass through the capitate carpal bone [21]. Research has shown that the 2 DOF in fact occurs through four different axes. The wrist flexion axis is different to the extension axis. Likewise, the radial deviation axis is different to the ulnar deviation axis. However, if the 2 DOF are each considered to have one axis each, there is a slight offset of approximately 5 mm between the two orthogonal axes. The SUEFUL-7 exoskeleton has taken this 5 mm axes offset into account [22].

Researchers have been incorporating more DOF into exoskeletons, allowing a larger variety of upper limb movements. Current upper limb exoskeletons focus on movements of the shoulder, elbow and/or wrist complex (Table 1). Several researchers have developed exoskeletons which include movements of the 2 DOF sternoclavicular joint at the shoulder complex. The MGA [23], ARMin III (Fig. 3c) [18] and IntelliArm [24] have implemented an actuated DOF for shoulder elevation/depression. The MEDARM has included actuation for both shoulder elevation/depression and retraction/protraction, allowing 5 DOF of actuated movement at the shoulder complex [25]. Other groups have opted to use passive DOF for the sternoclavicular joint [22,24,26]. Passive DOF allows the sternoclavicular joint to move freely but eliminates the ability to generate actuation forces at the joint.

Most upper limb exoskeletons have covered movements from the shoulder to the wrist joint but have not included additional DOF for finger movements. Although hand rehabilitation devices have been developed for finger movements [41], a complete upper limb exoskeleton with actuated DOF for the shoulder, elbow, wrist, and finger joints can enable more effective functional and ADL exercises. Among the many exoskeletons, the IntelliArm has incorporated a DOF for hand opening and closing in addition to DOF for the shoulder, elbow and wrist joints [24]. This exoskeleton has a total of 8 actuated DOF and 2 passive DOF. There is currently no exoskeleton device that can actuate all DOF of the upper limb. The majority of devices have been designed to actuate only the glenohumeral, elbow and wrist joints with a few devices that have also included DOF for the sternoclavicular joint. To enable an exoskeleton to operate in the entire range of motion of the human limb, either actuated or passive DOF needs to be incorporated for

Table 1
DOF of upper limb rehabilitation exoskeletons.

Exoskeleton name	Actuated DOF	Shoulder			Elbow			Wrist		Hand	Actuation
		Elev/Dep	Ret/Prot	Flex/Ext	Abd/Add	Med/Lat Rot	Flex/Ext	Pro/Sup	Flex/Ext	Rad/Uln Dev	
IntelliArm [24,27]	8	A	P	A	A	A	A	A	A	A	Electric motors
SUEFUL-7 [22,28]	7	P	-	A	A	A	A	A	A	-	Electric motors
CADEN-7 [29,30]	7	-	-	A	A	A	A	A	A	A	Electric motors
ExoKob [31]	7	-	-	A	A	A	A	A	A	A	Electric motors
ARMin III [18]	6	C	-	A	A	A	A	-	-	-	Electric motors
MEDARM [25]	6	A	A	A	A	A	A	-	-	-	Electric motors
MGA [23]	6	A	-	A	A	A	A	-	-	-	Electric motors
ABLE [32]	4	-	-	A	A	A	A	P	-	-	Electric motors
RehabExos [33]	4	-	-	A	A	A	A	A	-	-	Electric motors
WOTAS [34]	3	-	-	-	-	-	A	A	-	-	Electric motor
mPower	1	-	-	-	-	-	A	A	-	-	PMA
SRE [35,36]	7	-	-	A	A	A	A	A	A	A	PMA (unpaired)
RUPERT IV [37]	5	-	-	U	-	U	U	U	U	-	PMA
Hand Mentor	1	-	-	-	-	-	-	-	-	-	Pneumatic actuators
BONES [38]	4	-	-	A	A	A	A	-	-	-	Hydraulic disk brakes
Dampace [39]	4	P	-	A	A	A	A	-	-	-	Linear springs
WREX [40]	4	-	-	A	A	A	A	-	-	-	

A: actuated joint; P: unactuated passive joint; U: joint with unidirectional actuation; C: coupled with another joint.

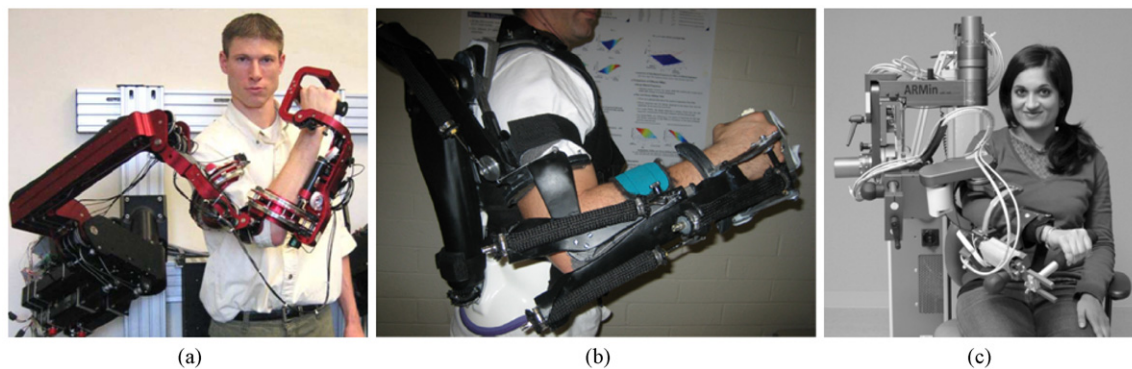


Fig. 3. Upper limb exoskeletons. (a) CADEN-7 [30]; (b) RUPERT IV [37]; (c) ARMin III [18].

each joint, including the sternoclavicular joint, glenohumeral joint, elbow joint, wrist joint, and finger joints.

3.1.1. The mechanical singularity problem

Robots with multiple rotary joints may possess configurations which causes a DOF to be lost. This occurs in configurations where the axes of two rotary joints align with each other. In the case of a 7 DOF upper limb exoskeleton, singularities can occur in postures where two rotational axes of the shoulder gimbal joint align and when the shoulder medial/lateral rotation axis aligns with the forearm pronation/supination axis at full elbow extension [30]. The later can be resolved by attaching the exoskeleton to the user's upper arm and forearm so that the angular position of medial/lateral rotation can be differentiated from pronation/supination. However, this approach cannot be used for the singular configurations of the exoskeleton shoulder joints. The CADEN-7 [30], MGA [23] and MEDARM [25] exoskeletons have been designed so that the singular configurations of the shoulder joints occur at a posture that is least likely to interfere with performing rehabilitation tasks. This does not completely solve the problem as singular configurations can still occur within the upper limb workspace.

3.1.2. Use of redundant DOF

Misalignment between the exoskeleton and the human limb can cause many problems such as the generation of undesirable interaction forces and inaccurate sensor measurements. Some research groups have reduced the degree of misalignment by including redundant DOF into the exoskeleton structure [22,24,26]. These joints are passive and are free to translate or rotate. By integrating these into the exoskeleton structure, the interaction forces caused by misalignment will adjust the structure to minimise the misalignment. In other words, the exoskeleton structure automatically self-corrects the misalignment. As mentioned in Section 3.1, several groups have used redundant passive DOF for the sternoclavicular joint. This may be a feasible approach since the sternoclavicular joint only undergoes small movements. The redundant DOF aligns the exoskeleton's shoulder joint with the user's glenohumeral joint during movements of the sternoclavicular joint. However, force generation for the sternoclavicular joint is not possible using this method due to its passive nature. Apart from correcting misalignment, redundant DOF can be used for other purposes. Using additional DOF may provide a solution for the mechanical singularity problem, reduce joint speeds during motion, and allow adjusting of the robot's size to match that of the user [42].

3.2. Human–robot interface (HRI)

As exoskeletons are physically coupled to the human limb, effective HRI is of utmost importance. Devices described in literature

have taken little consideration of the location of the mechanical HRI and the size of the contact area. Choosing interface locations that have a high pain tolerance to pressure can improve the user's safety and comfort [43]. Avoiding locations with high soft tissue content can provide a more stable attachment, resulting in better transfer of load forces. In addition, modelling the mechanical properties of the soft tissue at the HRI and incorporating this into the control model can improve control performance.

Other interfaces applicable to exoskeletons include EMG, visual and haptic interfaces. Exoskeletons which use EMG signals are discussed in Section 3.5. Vision sensors have been used in the control of assistive exoskeletons. Kiguchi et al. worked on an assistive exoskeleton which modifies the user's motion based on environmental information obtained from sonar sensors and stereo camera [44]. Baklouti et al. proposed the use of face and mouth gestures as control commands for an exoskeleton [45]. Current exoskeletons have limited haptic interfaces to provide touch sensations to the user's skin. Kapur et al. have used vibration actuators to generate sensations at different points on the user's arm to guide it through rehabilitation movements [46]. De Rossi et al. have been developing wearable garments using electroactive polymers which allow strain sensing and actuation [47]. Although these haptic devices are not exoskeletons, their features can be integrated into exoskeletons to enhance rehabilitation, especially in virtual games and exercises.

3.3. Actuation

The majority of existing upper limb exoskeletons are actuated by electromagnetic motors. Recently, there has been increased interest in the use of pneumatic muscle actuators (PMA). PMA actuators can only generate a tension force through contraction, therefore a pair of PMA are often used for each DOF to generate bidirectional movement [48]. PMA has several advantages over electromagnetic motors with the most significant being its high power-to-weight ratio. The soft nature of PMA makes the exoskeleton compliant and inherently safer to wear. However, PMA exhibit non-linear actuation characteristics making them more difficult to control. They also have a relatively low bandwidth of 5 Hz which limit the rate at which they can respond to command signals. Caldwell et al. have found that the bandwidth can be increased several folds by reducing the dead volume inside the PMA by the addition of filler materials and ensuring effective air flow [49]. Several upper limb exoskeletons in literature have used PMA [35,37,50]. The lightweight RUPERT IV exoskeleton (Fig. 3b) is a portable exoskeleton that uses unpaired PMA to provide movement for 5 DOF of the upper limb [37]. However, the joints can only be actuated in one direction since only one PMA is used for each DOF. The commercially available Hand Mentor uses a PMA for actuating wrist flexion/extension movement.

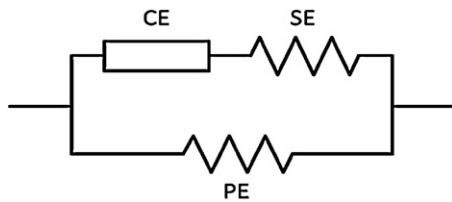


Fig. 4. Hill's three element muscle model. The model consists of a contractile element (CE), a series elastic element (SE) and a parallel elastic element (PE).

Other actuators of relevance to exoskeletons are smart materials. De Rossi et al. have integrated electroactive polymeric materials into wearable garments [47]. A sensorised shirt and glove have been developed which uses conductive elastomer sensors to identify the posture of the wearer's upper limb. The group is working to develop garments which consist of dielectric elastomer actuators.

Passive exoskeletons (not to be confused with passive joints) use actuators which are only able to generate resistive force. These exoskeletons have a lower weight compared to motor-actuated active exoskeletons as well as inherent safety. However, passive exoskeletons cannot actively assist movement so they are limited to providing resistive exercises and gravity balancing. Examples of passive exoskeletons include the Dampace which uses hydraulic disk brakes to generate controlled resistive torques for rehabilitation training [39] and the WREX which uses springs to negate the effects of gravity so that the patient can move the arm with minimal effort [40].

3.4. Modelling for control

Modelling of the upper limb can be categorised into dynamic modelling and muscle modelling. In dynamic modelling, the limb is treated as a mechanical system with rigid links joined together at rotary joints. This model predicts torques produced by inertial, gravitational, Coriolis and centrifugal effects [42]. The general form of the equation of motion is:

$$\tau = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \quad (1)$$

where τ is the joint torque vector, $M(\theta)$ is the inertia matrix, $V(\theta, \dot{\theta})$ is the Coriolis and centrifugal vector, and $G(\theta)$ is the gravity vector. Perry et al. have found that the forces due to gravitational effects are much larger than centrifugal, Coriolis and inertial loads [51].

A muscle model is used to predict the moment developed by the muscle as a function of muscle activation level and joint kinematics [52]. Researchers have used two main approaches to build muscle models: a black box approach and a phenomenological-based approach. One black box approach is to use a neural network to map an input set to an output set without utilising any formulation of muscle functionality [52]. A set of known inputs and outputs is used to train the neural network to predict the output given a set of arbitrary input values. Phenomenological-based approaches commonly use a Hill-based muscle model derived from the original model proposed by Hill [53] (Fig. 4). Comparison between a neural network model and a Hill-based model indicated that the neural network model made a more accurate prediction than the Hill-based model [52]. However, the performance of a neural network model is very task dependent since it relies on the information available in the training set. As a consequence, neural network models lose their effectiveness when performing tasks outside the scope of the training set or when applied to different subjects. In contrast, the formulation of the Hill-based model is rather complex and because the model is universal, it does not take into consideration the differences between subjects. Gopura and Kiguchi have used a fuzzy neural network model [54] while Perry et al. have

used a Hill-based model with genetic algorithm optimisation [55] in their implementation of EMG control for an upper limb exoskeleton (refer to Section 3.5.1).

3.5. Exoskeleton control

Effective control strategies are necessary for the exoskeleton to operate harmoniously with the human limb. Common strategies include position control and impedance control [22,23,29,56,57]. Many devices have reduced the negative effects of gravitational and frictional forces with gravity and friction compensation controllers [18,23,29,33,39]. Several exoskeletons have also used admittance control [23,57]. Recently, researchers are beginning to use more advanced control. Rahman et al. used PD control for their exoskeleton's passive mode while using a neuro-fuzzy based biological controller for active assist mode [58]. Rahman et al. have also used nonlinear computed torque control [31] and nonlinear sliding mode control [59] for trajectory tracking of the ExoRob exoskeleton. A bio-inspired controller based on the equilibrium point hypothesis (EPH) has been proposed for the NEURO exoskeleton [60,61]. The EPH, also known as the λ model for motor control, suggests that human motion involves a constantly shifting equilibrium position along the desired movement trajectory [62].

EMG signals provide an indication of muscle activation and are measured using electrodes attached onto the skin above the muscles. Several groups have used EMG signals for the control of an exoskeleton [54,55,58,63]. Many of the commercial exoskeleton-type devices also use EMG for control, including the mPower, Hand Mentor, and Robot Suit HAL-5. Ando et al. have used EMG signals to identify voluntary movement from a tremor patient to control an exoskeleton [64]. EMG signals have also been used to estimate the dynamics of the limb [65,66]. This information can be useful in creating a unique model of the user's limb.

3.5.1. Adaptive control

Adaptive control strategies can provide many benefits for exoskeletons as the controller can be automatically tuned for the variability between each patient as well as for the individual patient's changing needs. Despite this, the use of adaptive control for upper limb exoskeletons has not been widely adopted.

EMG measurements vary between individuals and can also vary on the same person due to offsets in electrode placement, fatigue [67], and other factors. As such, adaptive strategies and effective design and placement of the electrodes are required to account for these variations. A few researchers have used adaptive control strategies for EMG signal control of an upper limb exoskeleton. Kiguchi et al. have worked on several EMG controlled exoskeletons which adapt to the changing EMG signal levels of the user [22,28,54]. The movements of the exoskeleton are generated according to the user's motion intention to provide assistance to the upper limb. The fuzzy-neuro control method used is a combination of flexible fuzzy control and adaptive neural network control. The surface EMG signals of the user's muscles and the forces/torques measured from the exoskeleton's sensors are used as input information for the controllers. This information is used to provide torque commands to the exoskeleton to generate assistive forces. The control method consists of multiple fuzzy-neuro controllers which are activated according to the angles of the forearm and the wrist. Multiple controllers are necessary since activation levels of the muscles change according to the angles of forearm and wrist motions. Perry et al. also used a method to adapt an EMG controlled exoskeleton to different users [55]. In this case, genetic algorithm (GA) was used to optimise the parameters of Hill-based muscle models called myoprocessors. The advantage of GA is that they can deal with very large search spaces which reduce the risk of finding solutions that are only locally optimal.

The RUPERT IV exoskeleton invoked an iterative learning controller to overcome the highly non-linear nature of the PMA actuators and the patient's limb, as well as to adapt to different subjects for performing different reaching tasks in passive therapy mode [37]. Adaptive control algorithms have also been used for the MIT-MANUS [9] and ARM Guide [68] end-effector robots to adapt the device to the user's ability in order to provide a training task of appropriate difficulty.

There are many parameters which vary between patients including EMG signals, the mechanical properties of muscles and connective tissue, the effect of soft tissue on load transfer at the HRI, and the type and degree of weakness of each individual muscle. Adaptation to these parameters should be considered to achieve optimal performance of an exoskeleton for an individual user. Efficient calibration of exoskeletons to different users is an important step in enabling these devices to be used in practice.

4. Discussion

Recent technological advances have enabled the development of feasible exoskeleton robots. Modelling software has allowed exoskeletons to be tested in simulations before they are fabricated, allowing rapid prototype development. Biomechanics modelling allow the exoskeleton to mimic the dynamics of the human limb. Sensor technologies, control strategies and computing power have advanced to the extent where they are no longer major obstacles. However, actuator and power supply technologies still have limitations. Current actuators are unable to provide both a high power-to-weight ratio and high bandwidth while modern power supplies have insufficient energy density. PMA has a high power-to-weight ratio but lack bandwidth while motors have sufficient bandwidth but have a poor power-to-weight ratio. Current mobile exoskeleton robots rely on a lower limb exoskeleton to carry the weight of the actuators and power supply. Although, this has been shown to be a feasible approach with the recent success of the full-body HAL-5 exoskeleton for assisting the elderly and physically weak [69], improvements on the weight and efficiency of actuators and power supplies are still needed to achieve better exoskeleton performance. Another limitation is the singular configurations present in an exoskeleton's 3 DOF shoulder complex which occurs when two rotary joints align with each other, resulting in the loss of 1 DOF. The current method used to address the problem merely shifts the configuration to an uncommon posture rather than eliminating the configuration from the upper limb workspace.

There is limited consideration of the interactions between the exoskeleton and the human user. The mechanical HRI locations and interface area for optimal load transfer and comfort have not been considered in current exoskeletons. Mechanical interfaces in regions with a high pain tolerance can improve the user's safety and comfort while attachments on stable body structures with low compliance improves load transfer between the exoskeleton and the human body. Locations for attaching EMG electrodes also need to be considered to optimise the quality of the muscle signal measurements. However, there will evidently be variations in mechanical and neuromuscular characteristics between different subjects. In addition, the attachment locations of mechanical interfaces and EMG electrodes will inevitably vary each time the exoskeleton is worn. To enable better use of exoskeletons in practice, the devices need to be able to easily adapt to these variations without long calibration downtimes. Among the few upper limb devices that have used some form of adaptive strategy, adaptations have been used for the user's EMG signals, severity of impairment, inter-user variability and system non-linearity. Additional research is required to explore the use of a wider variety of adaptive strategies and further improve the user friendliness as well as the performance of exoskeletons.

One of the first clinical trials for upper limb rehabilitation exoskeletons is underway with the ARMin III exoskeleton [18]. Although no clinical data is available for exoskeletons yet, clinical results are available for some of the older end-effector type robots which provide strong evidence that robotic therapy has a beneficial effect on motor function [70]. However, comparing clinical data is rather difficult as different groups use different devices, control strategies, intervention strategies, and assessment criteria. There are many patient specific parameters that can affect the outcome of the treatment which may also need to be taken into consideration. There are currently insufficient guidelines and tools used in clinical evaluations of robotic therapy, and to some degree in conventional therapy, which is limiting the amount of quality data that can be acquired. Many assessment methods, such as the assessment of posture, are based on subjective impressions [71] which makes it difficult to justify the effectiveness of therapy treatments. Efforts should focus on developing and refining these guidelines and tools to ensure researchers can get as much reliable data as possible out of clinical evaluations. With better data, the effects of variations in the therapy and the patient on motor and functional recovery can be better understood. This will enable the development of more effective rehabilitation exoskeletons and intervention strategies. Exoskeleton technologies have the potential to initiate new areas of research as well as support existing research work. New approaches to rehabilitation therapy and patient assessment may be discovered and a better understanding of the human neuromuscular system can be achieved.

One promising approach for patient treatment is the application of task-based exercises in physiotherapy. There is evidence that suggests task-based therapy specifically designed to deal with lost abilities produce better results than resistance strengthening exercises [5]. However, realistic task-based exercises are difficult to achieve with manual therapy methods. Exoskeletons have the ability to accurately control multiple joints at the same time, enabling them to produce more realistic task-based exercises for the patient. In addition, studies have found that therapy is more effective when the patient exerts voluntary effort [72] in intensive and frequent exercises [5], much like recreational exercises. Incorporating therapy exercises into virtual games can make therapy more enjoyable, thus motivating the patient to put in effort and encouraging more exercise. In addition, the use of virtual reality enables more realistic task-based exercises to be performed. The concept of using virtual games to provide therapy exercises has already been used with a number of exoskeletons [17,23,39,56,57]. The next step is to design games based on physiotherapy principles and allow the games to be adjusted to better match the patient's level of motor deficiency. In the future, this concept can be extended to teach healthy individuals more sophisticated movements such as those in sports or occupational tasks. In the entertainment sector, exoskeletons can provide a more interactive gaming experience where the movement of the player's arm can be mimicked by the arm of a game character and the physical interactions of the game character can be felt by the player through the exoskeleton.

Acknowledgement

The authors would like to acknowledge the support of The University of Auckland Council in funding this research effort.

Conflict of interest

The authors declare no conflict of interest.

References

- [1] Donnan GA, Fisher M, Macleod M, Davis SM. Stroke. *The Lancet* 2008;371:1612–23.
- [2] Annual Report 2009. Stroke Foundation of New Zealand Inc., 2010.
- [3] Khawaja M, Thomson N. Population ageing in New Zealand, 2000.
- [4] Teasell RW, Kalra L. What's new in stroke rehabilitation: back to basics. *Stroke* 2005;36:215–7.
- [5] Teasell RW, Kalra L. What's new in stroke rehabilitation. *Stroke* 2004;35:383–5.
- [6] Huang VS, Krakauer JW. Robotic neurorehabilitation: a computational motor learning perspective. *Journal of NeuroEngineering and Rehabilitation* 2009;6.
- [7] Laver K, George S, Ratcliffe J, Crotty M. Virtual reality stroke rehabilitation—hype or hope? *Australian Occupational Therapy Journal* 2011;58:215–9.
- [8] Hogan N, Krebs HI, Charnnarong J, Srikrishna P, Sharon A. MIT-MANUS: a workstation for manual therapy and training I. In: *IEEE international workshop on robot and human communication*. 1992. p. 161–5.
- [9] Krebs HI, Palazzolo JJ, Dipietro L, Ferraro M, Krol J, Rannekleiv K, et al. Rehabilitation robotics: performance-based progressive robot-assisted therapy. *Autonomous Robots* 2003;15:7–20.
- [10] Burgar CG, Lum PS, Shor PC, Van Der Loos HFM. Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience. *Journal of Rehabilitation Research and Development* 2000;37:663–73.
- [11] Loureiro R, Amirabdollahian F, Topping M, Driessen B, Harwin W. Upper limb robot mediated stroke therapy—GENTLE/s approach. *Autonomous Robots* 2003;15:35–51.
- [12] Krebs HI, Hogan N, Volpe BT, Aisen ML, Edelstein L, Diels C. Overview of clinical trials with MIT-MANUS: a robot-aided neuro-rehabilitation facility. *Technology and Health Care* 1999;7:419–23.
- [13] Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Archives of Physical Medicine and Rehabilitation* 2002;83:952–9.
- [14] Lum PS, Burgar CG, Shor PC. Evidence for improved muscle activation patterns after retraining of reaching movements with the MIME robotic system in subjects with post-stroke hemiparesis. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 2004;12:186–94.
- [15] Lum PS, Burgar CG, Van Der Loos M, Shor PC, Majmundar M, Yap R. MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: a follow-up study. *Journal of Rehabilitation Research and Development* 2006;43:631–42.
- [16] Coote S, Murphy B, Harwin W, Stokes E. The effect of the GENTLE/s robot-mediated therapy system on arm function after stroke. *Clinical Rehabilitation* 2008;22:395–405.
- [17] Frisoli A, Borelli L, Montagner A, Marcheschi S, Procopio C, Salsedo F, et al. Arm rehabilitation with a robotic exoskeleton in Virtual Reality. In: *International conference on rehabilitation robotics*. 2007. p. 631–42.
- [18] Nef T, Guidali M, Riener R. ARMin III—arm therapy exoskeleton with an ergonomic shoulder actuation. *Applied Bionics and Biomechanics* 2009;6:127–42.
- [19] Tondu B. Estimating shoulder-complex mobility. *Applied Bionics and Biomechanics* 2007;4:19–29.
- [20] Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, Laprade RF. Motion of the shoulder complex during multiplanar humeral elevation. *Journal of Bone and Joint Surgery-Series A* 2009;91:378–89.
- [21] Neu CP, Crisco JJ, Wolfe SW. In vivo kinematic behavior of the radio-capitate joint during wrist flexion-extension and radio-ulnar deviation. *Journal of Biomechanics* 2001;34:1429–38.
- [22] Gopura RARC, Kiguchi K, Yi Y, SUEFUL-7: a 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control. In: *IEEE/RSJ international conference on intelligent robots and systems*. 2009. p. 1126–31.
- [23] Carignan C, Tang J, Roderick S. Development of an exoskeleton haptic interface for virtual task training. In: *IEEE/RSJ international conference on intelligent robots and systems*. 2009. p. 3697–702.
- [24] Ren Y, Park HS, Zhang LQ. Developing a whole-arm exoskeleton robot with hand opening and closing mechanism for upper limb stroke rehabilitation. In: *IEEE international conference on rehabilitation robotics*. 2009. p. 761–5.
- [25] Ball SJ, Brown IE, Scott SH. MEDARM: a rehabilitation robot with 5DOF at the shoulder complex. In: *IEEE/ASME international conference on advanced intelligent mechatronics*. 2007.
- [26] Stienen AHA, Hekman EEG, van der Helm FCT, van der Kooij H. Self-aligning exoskeleton axes through decoupling of joint rotations and translations. *IEEE Transactions on Robotics* 2009;25:628–33.
- [27] Park HS, Ren Y, Zhang LQ. IntelliArm: an exoskeleton for diagnosis and treatment of patients with neurological impairments. In: *Biennial IEEE/RAS-EMBS international conference on biomedical robotics and biomechanics*. 2008. p. 109–14.
- [28] Kiguchi K, Rahman MH, Sasaki M, Teramoto K. Development of a 3DOF mobile exoskeleton robot for human upper-limb motion assist. *Robotics and Autonomous Systems* 2008;56:678–91.
- [29] Perry JC. Design and development of a 7 degree-of-freedom powered exoskeleton for the upper limb [dissertation]. United States, Washington: University of Washington; 2006.
- [30] Perry JC, Rosen J, Burns S. Upper-limb powered exoskeleton design. *IEEE/ASME Transactions on Mechatronics* 2007;12:408–17.
- [31] Rahman MH, Saad M, Kenné JP, Archambault PS. Modeling and control of a 7DOF exoskeleton robot for arm movements. In: *IEEE international conference on robotics and biomimetics*. 2009. p. 245–50.
- [32] Garrec P, Fricconneau JP, Méasson Y, Perrot Y. ABLE, an innovative transparent exoskeleton for the upper-limb. In: *IEEE/RSJ international conference on intelligent robots and systems*. 2008. p. 1483–8.
- [33] Verthey R, Frisoli A, Dettori A, Solazzi M, Bergamasco M. Development of a new exoskeleton for upper limb rehabilitation. In: *IEEE international conference on rehabilitation robotics*. 2009. p. 188–93.
- [34] Rocon E, Belda-Lois JM, Ruiz AF, Manto M, Moreno JC, Pons JL. Design and validation of a rehabilitation robotic exoskeleton for tremor assessment and suppression. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 2007;15:367–78.
- [35] Caldwell DG, Tsagarakis NG, Kousidou S, Costa N, Sarakoglou I. Soft exoskeletons for upper and lower body rehabilitation—design, control and testing. *International Journal of Humanoid Robotics* 2007;4:549–73.
- [36] Kousidou S, Tsagarakis N, Caldwell DG, Smith C. Assistive exoskeleton for task based physiotherapy in 3-dimensional space. In: *1st IEEE/RAS-EMBS international conference on biomedical robotics and biomechanics*. 2006. p. 266–71.
- [37] Balasubramanian S, Wei HR, Perez M, Shepard B, Koeneman E, Koeneman J, et al. Rupert: an exoskeleton robot for assisting rehabilitation of arm functions. In: *2008 virtual rehabilitation. IWVR*. 2008. p. 163–7.
- [38] Klein J, Spencer SJ, Allington J, Minakata K, Wolbrecht ET, Smith R, et al. Biomimetic orthosis for the neurorehabilitation of the elbow and shoulder (BONES). In: *Biennial IEEE/RAS-EMBS international conference on biomedical robotics and biomechanics*. 2008. p. 535–41.
- [39] Stienen AHA, Hekman EEG, Van Der Helm FCT, Prange GB, Jannink MJA, Aalsma AMM, et al. Dampace: dynamic force-coordination trainer for the upper extremities. In: *IEEE 10th international conference on rehabilitation robotics*. 2007. p. 820–6.
- [40] Rahman T, Sample W, Jayakumar S, King MM, Wee JY, Seliktart R, et al. Passive exoskeletons for assisting limb movement. *Journal of Rehabilitation Research and Development* 2006;43:583–9.
- [41] Balasubramanian S, Klein J, Burdet E. Robot-assisted rehabilitation of hand function. *Current Opinion in Neurology* 2010;23:661–70.
- [42] Pons JL. Wearable robots: biomechatronic exoskeletons. Chichester, England/Hoboken, NJ: John Wiley & Sons; 2008.
- [43] Pons JL. Rehabilitation exoskeletal robotics. *IEEE Engineering in Medicine and Biology Magazine* 2010;29:57–63.
- [44] Kiguchi K, Liyanage M. A study of a 4DOF upper-limb power-assist intelligent exoskeleton with visual information for perception-assist. In: *IEEE international conference on robotics and automation*. 2008. p. 3666–71.
- [45] Baklouti M, Monacelli E, Guitteny V, Couvet S. Intelligent assistive exoskeleton with vision based interface. In: *International conference on smart homes and health telematics*. 2008. p. 123–35.
- [46] Kapur P, Premakumar S, Jax SA, Buxbaum LJ, Dawson AM, Kuchenbecker KJ. Vibrotactile feedback system for intuitive upper-limb rehabilitation. In: *Joint EuroHaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems*. 2009. p. 621–2.
- [47] De Rossi D, Carpi F, Lorussi F, Scilingo EP, Tognetti A. Wearable kinesthetic systems and emerging technologies in actuation for upperlimb neurorehabilitation. In: *Annual international conference of the IEEE engineering in medicine and biology society*. 2009. p. 6830–3.
- [48] Davis S, Tsagarakis N, Canderle J, Caldwell DG. Enhanced modelling and performance in braided pneumatic muscle actuators. *International Journal of Robotics Research* 2003;22:213–27.
- [49] Davis S, Canderle J, Artrit P, Tsagarakis N, Caldwell DG. Enhanced dynamic performance in pneumatic muscle actuators. In: *IEEE international conference on robotics and automation*. 2002. p. 2836–41.
- [50] Zhang JF, Yang CJ, Chen Y, Zhang Y, Dong YM. Modeling and control of a curved pneumatic muscle actuator for wearable elbow exoskeleton. *Mechatronics* 2008;18:448–57.
- [51] Perry JC, Powell JM, Rosen J. Isotropy of an upper limb exoskeleton and the kinematics and dynamics of the human arm. *Applied Bionics and Biomechanics* 2009;6:175–91.
- [52] Rosen J, Fuchs MB, Arcan M. Performances of hill-type and neural network muscle models—toward a myosignal-based exoskeleton. *Computers and Biomedical Research* 1999;32:415–39.
- [53] Hill AV. The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London Series B-Biological Sciences* 1938;126:136–95.
- [54] Gopura RARC, Kiguchi K. Electromyography (EMG)—signal based fuzzy-neuro control of a 3 degrees of freedom (3DOF) exoskeleton robot for human upper-limb motion assist. *Journal of the National Science Foundation of Sri Lanka* 2009;37:241–8.
- [55] Cavallaro EE, Rosen J, Perry JC, Burns S. Real-time myoprocessors for a neural controlled powered exoskeleton arm. *IEEE Transactions on Biomedical Engineering* 2006;53:2387–96.
- [56] Kousidou S, Tsagarakis NG, Smith C, Caldwell DG. Task-orientated biofeedback system for the rehabilitation of the upper limb. In: *International conference on rehabilitation robotics*. 2007. p. 376–84.
- [57] Nef T, Mihej M, Riener R. ARMin: a robot for patient-cooperative arm therapy. *Medical and Biological Engineering and Computing* 2007;45:887–900.

- [58] Rahman MH, Kiguchi K, Rahman MM, Sasaki M. Robotic exoskeleton for rehabilitation and motion assist. In: International conference on industrial and information systems. 2006. p. 241–6.
- [59] Rahman MH, Saad M, Kenné JP, Archambault PS. Exoskeleton robot for rehabilitation of elbow and forearm movements. In: Mediterranean conference on control and automation. 2010. p. 1567–72.
- [60] Lenzi T, De Rossi S, Vitiello N, Chiri A, Roccella S, Giovacchini F, et al. The neuro-robotics paradigm: NEURARM, NEUROExos, HANDEXOS. In: Proceedings of annual international conference of the IEEE engineering in medicine and biology society. 2009. p. 2430–3.
- [61] Sardellitti I, Cattin E, Roccella S, Vecchi F, Carrozza MC, Dario P, et al. Description, characterization and assessment of a bio-inspired shoulder joint-first link robot for neuro-robotic applications. In: IEEE/RAS-EMBS international conference on biomedical robotics and biomechatronics. 2006. p. 112–7.
- [62] Feldman AG, Levin MF. The origin and use of positional frames of reference in motor control. *Behavioral and Brain Sciences* 1995;18:723–806.
- [63] Lee MH, Son J, Kim JY, Kim YH. Development and assessment of an EMG-based exoskeleton system. In: IFMBE proceedings. 2010. p. 648–50.
- [64] Ando T, Watanabe M, Fujie MG. Extraction of voluntary movement for an EMG controlled exoskeletal robot of tremor patients. In: International IEEE/EMBS conference on neural engineering. 2009. p. 120–3.
- [65] Artemiadis PK, Kyriakopoulos KJ. Estimating arm motion and force using EMG signals: on the control of exoskeletons. In: IEEE/RSJ international conference on intelligent robots and systems. 2008. p. 279–84.
- [66] Ruiz AF, Rocon E, Forner-Cordero A. Exoskeleton-based robotic platform applied in biomechanical modelling of the human upper limb. *Applied Bionics and Biomechanics* 2009;6:205–16.
- [67] Öberg T. Muscle fatigue and calibration of EMG measurements. *Journal of Electromyography and Kinesiology* 1995;5:239–43.
- [68] Kahn LE, Rymer WZ, Reinkensmeyer DJ. Adaptive assistance for guided force training in chronic stroke. In: Annual international conference of the IEEE engineering in medicine and biology society. 2004. p. 2722–5.
- [69] Guizzo E, Goldstein H. The rise of the body bots. *IEEE Spectrum* 2005;42:42–8.
- [70] Hayward K, Barker R, Brauer S. Interventions to promote upper limb recovery in stroke survivors with severe paresis: a systematic review. *Disability and Rehabilitation* 2010;32:1973–86.
- [71] Fortin C, Ehrmann Feldman D, Cheriet F, Labelle H. Clinical methods for quantifying body segment posture: a literature review. *Disability and Rehabilitation* 2011;33:367–83.
- [72] Lotze M, Braun C, Birbaumer N, Anders S, Cohen LG. Motor learning elicited by voluntary drive. *Brain* 2003;126:866–72.