Upper Body Rehabilitation: A Survey

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1 Introduction

The Impact of disabilities on society is great, not only on financial costs but also the invaluable loss of human creativity and productivity[19]. By providing prosthesis, exoskeletons or robotic assistance, some of this loss can be regained. Over the past decade there has been a significant increase in the research and development of medical prosthesis and rehabilitative technology, such as supportive robotics and exoskeletons.

Brain and Spinal injury are the two biggest contributors to the loss of upper body control. Improved medical treatment of the complications caused by acute stroke has contributed to decreased mortality, but 90% of the survivors have significant neurological deficits[21]. The most common consequence of stroke is hemiparesis (muscle weakness on only one side of the body) of the limbs contralateral to the brain lesion, hemiparesis can range from mild weakness to complete paralysis. It has been estimated that 30% to 66% of stroke survivors are unable to functionally use the affected upper extremity for activities of daily living (ADLs) after therapy[23].

The most effective ingredients for improving function after stroke are 1) Task-specific practice and 2) Repetition. This is where robotics becomes useful, as they are ideally suited to repetitive tasks. One of the most basic decisions of a physiotherapist is whether or not to provide mechanical assistance during training movements for patients who are too weak or uncoordinated to move successfully by themselves. The costs and shortages of physiotherapist, motivates the construction of rehabilitative robotics that can alleviate the strain on both the therapist and the health service.

Robotics provides time saving benefits to physiotherapists, while subsequently providing entertainment to the patient in the form of computer generated 3D environments, which provide visual, auditory and haptic(touch) interactions. This provides patients with entertaining and motivational games while also preceding through their therapy. This also gives effective feedback to the therapist and allows them to monitor the progress[19]. Since upper limb and hand disabilities are rarely considered life threatening, they rate relatively low on the priority list for urgent medical assistance[19]. There is plenty of research confirming that robotics has positive influence in rehabilitation [5][35] [31].

In recent years rehabilitative robots have began to leave the hospital in more portable forms, and provides future potential of having exoskeleton support in everyday activates and rehabilitative therapy. This review looks over upper body rehabilitative robotics and exoskeletons to see what is current available and where the future lies. The remainder of this review is broken down into 5 sections. Section 2 provides a background into robotic rehabilitation. Section 3 is view of current robotic upper body rehabilitative devices, Section 4 looks into upper body exoskeleton rehabilitative devices. Section 5 provides a discussion of rehabilitative devices and outlines potential. Section 6 concludes the review.

2 Background

The department of health estimates stroke costing to the national health services (NHS) about £8 billion a year in the uk [1], including the direct NHS cost £2.8 billion, and the wider economy costs £4.2 billion, associated with lost productivity, disability and informal care. Stroke is one of the top three causes of death in England and a leading
cause of adult disability. Approximately 110,000 strokes and a further 20,000 Transient Ischaemic Attacks ('mini strokes') occur in England every year, with the American Heart Association (2007) quoting 700,000 people a year, which costs the US an estimated 56 billion dollars a year in 2005.

There are at least 300,000 people in England living with moderate to severe disabilities as a result of stroke [33]. With hundreds of thousands more around the world. The majority of stroke patients survive if they are brought to hospital quickly, out of those survives a big portion of these have residual disabilities. With one person having a stroke every five minutes [1] and patients often needing one or more therapists, the health service has to bear high costs.

Patients with hemiparesis following stroke typically exhibit a decrease in muscle strength and coordination along with changes in tone. When patients with increased flexor tone or stiffness attempt to use the more affected hand, a common pattern is increased wrist flexion, which then weakens grip strength by means of passive forces on the extensor's. Previous studies have reported that 35 degrees of wrist extension is the optimal position to achieve maximal grip strength, and maximum force is decreased by approximately 75% when wrist extension is limited to 15 degrees [23]. Designing robots to constrain individuals to operate at optimal angles, while also providing strength-enhancing abilities would help to facilitate daily living.

At 6 months post stroke, about 65% of patients cannot incorporate their affected hand into their usual activities [31]. This is why early repetitive motion rehabilitation would be beneficial. Krebs et al. [13] gathered convincing evidence that nurture significantly impacts the speed of motor recovery in the paretic shoulder and elbow, and further concludes that robot therapy is effective in delivery necessary rehabilitative exercises. Followings these results, Krebs et al. developed a family of modular robots to aid in the rehabilitation of other muscle groups, this forms the MIT-MANUS group of robots described in Section 3. All modules are safe and stable which is essential for human centered robotics.

There is evidence that improvement in recovery can be achieved if neural organization is modified. Damaged neural pathways can be re instituted and neurons not normally involved in activity can be engaged [19], this is neuro-plasticity, and is user-dependant. In other words, intensive repetitive physiotherapy is able to modify neural organization and recover lost functional motor skills. This means the brain can adapt from lost functionality caused by stroke or perhaps even more extreme, a lost limb.

A bit less than half of the motor cortex of the human brain is devoted to the muscles of hands, arms and shoulders. This is usually illustrated with a drawing of a human figure draped over the side of the brain (Figure 1), body parts are sized proportional to the amount of brain devoted to their control. For the brain scan in Figure 2, Takahashi et al. showed that a grasp task is central to their therapy. Some significant increases appear in the activation volume over time within the stroke effected area in the left sensorimotor cortex, while the non-practiced supination task did not. This change was not accompanied by a task related increase in EMG, suggesting that its basis was altered brain organization rather then altered subject performance [9], demonstrating how motor reorganization can take place.

Upper body rehabilitation focuses on the arm, consisting of the shoulder, elbow, wrist and hand. Rehabilitation requires the full range of human motion, while also providing supportive assistance. In rehabilitation, a patient will attempt to make a movement while the therapist provides some form of support for the limb. Mechanical or robotic assistance can be used to complete the desired movement. Different forms of active-assist have been implemented with rehabilitation equipment ranging from simple overhead slings and arm
Figure 1: Sensory and Motor Cortex

Figure 2: Proof of brain reorganization

skateboards to sophisticated robotic devices. Robotics can provide the full flow of body movements, which can be calibrated to each individual and each disability. Robotic actuators then provide the supportive assistance needed for weaker individuals. Modeling the human shoulder is a complex process, it forms a ball and socket joint, giving it a wide range of motion. The elbow forms a simple 2-DOF motion lever joint, and the wrist is made from a ellipsoidal joint, i.e. a modified ball and socket joint in which movement is more restricted (All can be seen in Figure 3). Robotically recreating the functionality of these 3 joints, with sufficiently light materials while still providing power and the strength needed for long lasting operation. The human hand alone is an incredible piece of biological machinery consisting of 29 bones, 29 major joints, roughly 24-DOF of flexibility, more than 123 ligaments, and 35 muscles with 18 of those in the forearm and 17 in the hand. More than half of the bones in your body are found in your hands and feet making them the most complex supporting structure in the entire body. This is why there is currently not a single rehabilitative device capable of complete upper body support.

3 Rehabilitation Robotics

It is important for physically challenged individuals to keep active in their daily life. This not only prevents increased muscle loss but also has additional psychological benefits.
Being self sufficiency, i.e. not having to rely on others to feed you, bathe you and dress you, helps maintain and improve confidence. Returning functionality and improving a persons quality of life is the main goal of rehabilitation. Currently there are shortages in physiotherapists which limits societies ability help the disabled. Rehabilitation is labor intensive and requires one on one interaction for long periods of time. Robotics provides a solution, and can alleviate some of the repetitive labor intensive physiotherapists tasks.

Repetitive physiotherapy is important for regaining motor control as it contributes towards regaining muscle strength and restoring range of motion. A number of upper body rehabilitative robots have been developed, many of which are described in the rest of this section. The major findings in robot centered rehabilitation come from two systems, namely the MIT-MANUS and MIME[19].

**MIT-MANUS**

The rehabilitation robot developed by Krebs et al[13] was focused on improving therapy aid, particularly as a tool for supporting and enhancing the effectiveness of therapists. The left side of Figure 4 shows the 1st rehabilitation robot MIT-MANUS. The MIT MANUS is a 2-DOF)robot for elbow and forearm motion. A 6-DOF force sensor is attached to the robot to control the motion by a personal computer. The computer also displays the task to perform for both the operator and subject via dedicated monitors. The robot operates in 15” by 18” workspace, and can apply impedance up to 4.2 N/mm which is the effectively a virtual wall. The robot can deliver forces up to 45N but is aimed for uses at 28N, which corresponds to a humans arm strength during elbow extension.
for a weak women.

The success of the MIT MANUS lead to a further development of a 1-DOF module. This provides vertical motion and force. A prototype is shown in the middle of Figure 4, providing 65N of force in the upward directions and 45N in the downward direction. It achieves a stiffness in excess of 10 N/mm, much more than is generally needed for rehabilitation therapy. An improvement in linear motor technology includes the reduced friction and eliminated backlash, as well as simplifying the controller and control system. The right of Figure 4 shows the module that allows for 19.4 inches of linear motion with a 65N upward and 45N downward force.

**Mirror Image Movement Enabler (MIME)**

Lum et al. [35] compared robot assisted rehabilitation against conventional techniques for upper-limb motor function after stroke. A test group evaluated rehabilitation assisted by a robot, and the control group followed conventional therapy. Lum et al. reported that the robot group had larger improvement in the proximal movement portion of fugal-Meyer test (which is a test procedure to measures the motor and sensory impairment), including larger gains in strength and larger increase in reach extent after 2 months. However after a six month follow up, both groups performed equally on the Fugl-Meyer test. The robot group did have larger improvement in the FIM test, which the Center For Outcome Measurement In Brain Injury states as the most widely accepted functional assessment measure in use in the rehabilitation community, and is viewed as the most useful for assessment of progress during inpatient rehabilitation.

The robotic assistant used in their study is called mirror image movement enabler (MIME). The system works by applying direct forces to the affected forearm during goal orientated therapy. A key feature of MIME is that patients at any level can use the system by repeatedly practicing movement patterns. As mentioned previously this is proven to have profound effects on recovering from brain injury.

The robot setup required a arm splint to be connected to the robot so that a user could place their arm in the splint. The forces that would usually be applied by the therapist would then be replaced by the robot manipulator. The 6 DOFs provided by the robot allows for a large range of positions and orientations in 3D space. Forces and torques where measured by a 6-axis sensor. A picture of the robot is shown in 5. This system allows for both assisted support movement and viscous resistive movement.

It has been found that chronic stroke subjects can have substantial increase in use of the affected limb in daily living when preforming constraint-induced therapy, which
involves intensive repetitive exercise of the affected limb while constraining the opposite limb. This results in positive re-organization in the motor cortex[35].

**InMotion 2.0 and 3.0.**

Based on the “MIT Manus”, the InMotion Shoulder and Elbow robot (shown in Figure 6 on the left) improves elbow and shoulder control. The benefits of the InMotion 2.0 Shoulder-elbow robot have been shown in multiple research studies involving patients with stroke, cerebral paralysis and other neurological conditions[42].

The robotic arm sits on a desktop, along with a computer monitor. The patient’s arm is positioned in a trough connected to the robotic arm. The computer prompts the patient to perform a task such as connecting the dots or drawing the hands of a clock, which is visually tracked on the screen. If the patient does not have the ability to move the upper extremity fully, the robot moves the arm for the person. If the patient can initiate the movement on their own, the robot turns itself off and allows the patient’s movement to continue.

The robotic arm performs four basic movements that are part of many therapy plans: passive, active assistive, active range of motion, and progressive resistance. These exercises, when combined with the purposeful and engaging computer games, allow patients to receive the repetition necessary (up to 1,000 per hour) to achieve the desired range of motion, strength, and ultimately increased function in the arm.

A further addition to the InMotion family is InMotion version 3.0, based on wrist rehabilitation. Interactive Motion Technologies [42] claim this to be The first-ever interactive wrist device for robotic therapy. The wrist robot allows 3D movements: pronation/supination, flexion/extension and radial and ulnar deviation. Employing both the Shoulder-Elbow Robot and the Wrist Robot researchers have observed significant improvement even in patients with severe chronic impairment.

**ReoGo**

ReoGo is a advanced robotic system for upper limb therapy created by Motorika (Israel), which facilitates 3D repetitive arm movements through the use of an advanced, fully motorized robotic arm. With a variety of interactive and stimulating games that imitate natural hand movements, in order to generate a fun yet rehabilitative environment. ReoGo is a portable wheeled based system and can be transported relatively easily. ReoGo is shown in Figure 7 [29]


ARM Guide uses a motor and chain drive to move the user’s hand along a linear rail. The linear rail can be oriented at different yaw and pitch angles to allow for reaching to different workspace regions. It is a counterbalanced robot so that it does not load the arm, and mechanically assists in reaching movements[22]. The device can assist or resist
movement, and can measure hand movement and force generation. The ARM Guide senses that movement has started and then moves the handle at a desired speed through the arm’s full passive range. A DC servo motor controls the position of the participant’s arm, optical encoders record the positions of the device in the reaching direction and around the yaw and elevation axes [34].

Significant improvements where noticed in movement ability, with both active-assist and unassisted training. Repetitive movement training is a viable strategy for improving impairment of hemiparetic upper extremity patients after chronic stroke, with or without a robotic device. The robotic assistance incorporated here did not provide any detectable benefits beyond the unassisted movement exercise, though interpretation of this result is limited by sample size, and to the specific assistance technique employed with the device.[22]

GENTLE/s

The GENTLE/s is focused on neuro and physical rehabilitation and particularly concentrates on developing; new, challenging and motivating therapies to aid the increase of sensory input, relearning stimulation in the brain, and achieve functional goals that improve independence and coordination [24]. The GENTLE/s approach utilizes haptic (tactile/touch) and Virtual Reality (VR) technologies. The System consists of a frame, a chair, a shoulder support mechanism, a wrist connection mechanism, an elbow orthosis,
two embedded computers, a large computer screen with speakers, an exercise table, a keypad and a 3-DOF haptic interface.

An Upper Extremity Motor Function Rehabilitation And Assessment System

Song et al [44] developed a upper extremity motor function rehabilitation and assessment system (left of Figure 10) which can be manipulated through a haptic device and inertia sensing. The system is small and light weight which makes it suitable for home-based rehabilitation. It improves patients quality of life by being able to work from home while also reducing therapist time and therefore the reduced cost to the national health services. The system uses its haptic and inertia controls to move a virtual reality based program.

A virtual curve path was designed whereby the user navigates using the force sensitive joystick (PHANTOM Omni) with the impaired limb while using a accelerometer on the non-impaired limb. The limited output torque of the phantom omni limits its usefulness for stronger individuals. This is why a further system was developed with a 6-axis force sensor installed on the hand of a robot (right of Figure 10). A virtual environment was created in the system, where the user is required to match the orientation and position of two objects by manipulating the robot hand. The limitation of the system is that it is big and difficult to use since it requires additional training time to adapt to perform the therapy.

4 Upper Body Power Assisted Rehabilitation Exoskeletons

Traditional rehabilitative robots use the same ingredients: a robotic arm, some form of force sensitive grip, or splint attachment that is able to move around in a 3D VR environment. However, a biological exoskeleton is an external skeleton that supports and protects an animal’s body, many exist in nature: crabs, turtles, armadillos. Humans have created their own exoskeletons for centuries, i.e. more commonly known as protective armor. In Bionics, an exoskeleton is a wearable robotic electro-mechanical device that can support a user body. It can provide performance enhancement to able bodied individuals, as well as provide motion support to weaker or disables users. Exoskeletal devices have been found to be a extremely useful form of rehabilitation, allowing users to perform natural rehabilitation therapy by doing everyday tasks aided by an exoskeleton.
The 1st documented exoskeleton dates back to an 1890 patent, the invention was a purely mechanical design, using springs to enhance a user’s running and jumping abilities. In the 1960’s a development by General Electric research, created the 1st powered exoskeleton. This was an enormous full bodied exoskeleton, and was created with the intention to drastically improve a user’s strength by a 1:25 ratio. More recent exoskeletons include the BLEEX - Berkeley Lower Extremity exoskeleton, agricultural assisting exoskeleton and the 1st commercially available exoskeleton, HAL (Hybrid Assistive Limb) which are shown in Figure 12.

Robotic exoskeletons have three main purposes: to develop assistive technology for the rehabilitative purposes, to develop advanced technologies to augment human abilities, and to enhance the mobility or dexterity of the world’s aging population. Currently, almost 20 per cent of the world population is over 65 and this figure is forecast to exceed to 35 per cent by 2050 [4]. Perry et al. further add that robotic exoskeleton can be deployed for tele-operation in hazardous environments.

Currently there are more lower limb than upper limb exoskeletons. This is due to a number of reasons, which gravitate towards: loss of lower limb functionality is more debilitating, lower body devices have less weight restrictions - as the weight can be more easily transferred to the ground, therefore on upper body exoskeletons a considerable
bulk of the weight would have to be applied to the shoulders if the exoskeleton had no physically connection to the ground to transfer the weight. In general, the upper body is significantly more complex as it includes the hand and forearm- making it more difficult to replicate lost functionality.

Lower limb and full bodied exoskeletons are able to focus the weight load through the exoskeleton legs. Figure 13 shows the weight distribution on a human wearing an exoskeleton. This is why most upper body robotics are either 1) extremely light so the user can manage the load, 2) Are fixed (stationary) exoskeletons which transfer the weight through the ground 3) Are Full bodied exoskeletons allowing transfer of the weight through the legs 4) Or attached to a moving structure like a wheel chair.

The main issues with upper body exoskeletons are (adapted from [43]) : 1) Size and Weight. 2) Accurate motion. 3) Safe operation as well as safe perception from a users viewpoint. 4) Reliable in all situations. 5) Easy maintenance. 6) Simple fitting and removal. 7) Comfortable and suitable for long term use. 8) Minimal/no movement restrictions. Ideally low engineering complexity and construction costs are expected.

Measuring the metabolic cost is a key performance measure, and demonstrates the effectiveness of the exoskeleton. By measuring oxygen consumption and carbon dioxide
production during normal activity and exoskeletal activity, it is possible to measure the physical exertion placed on a user during an activity. Many commercial available devices are low cost and portable, which makes it an excellent indicator of exoskeleton performance [11]. To compare, BLEEX consumes an average 1143W of hydraulic power during walking as well as 200W for electronic operation. While a similar sized human (75Kg) consumes 165W of metabolic power during walking [11]. Considering the complexity involved in upper body exoskeletons, the two following subsections has been divided into two: Upper Arm and Lower arm Exoskeletons.

4.1 Upper Arm Exoskeletons

This section gives an overview of Upper Arm Exoskeletons which support the shoulder and elbow. The shoulder and elbow, as shown in Figure 3 in the introductory section, consist of a Ball and socket joint and a hinge joint, hence the complexity is not difficult to understand. Below are descriptions of a few currently available upper arm exoskeletons, that could be used in rehabilitation.

**Armeo**

Armeo is a sustainable and powerful therapy concept for individuals who have suffered strokes, traumatic brain injuries or neurological disorders resulting in hand and arm impairment[15]. The Armeo rehabilitation robots are based on research evidence of brain plasticity. It comprises a modular line of three Armeo products all driven from a single software platform. The result is a comprehensive therapy concept which addresses different patient and therapeutic needs across the whole continuum of rehabilitation. All three versions are depicted in Figure 15 and descriptions are taken from the Hocoma website and technical documentation. Figure 14 explains how to determine the suitable version for a patient.

![Figure 14: Armeo Robotic exoskeletons selection](image)

**The Armeo Power**

The Armeo Power is a rehabilitative exercise device for upper extremity therapy. The main component of the ArmeoPower is a motorized arm orthosis, which is able to support the weight of a patient’s arm and to assist the patient during specific exercises in a large 3D workspace. The Armeo Power is intended for patients who have lost the function or have restricted function in their upper extremities caused by central nervous or peripheral neurogenic, spinal, muscular or bone-related disorders. It supports specific
exercises to increase the strength of muscles and the range of motion of joints in order to improve motor function.

The Armeo Power is made up of 6 actuated degrees of freedom, each with a motor and two angular sensors. Along with a hand grip with an integrated grip pressure sensor. The system is mounted on a mobile platform and weighs approximately 240Kg and requires a space of 3.5 x 3.5 x 2 m (l x w x h) [17]. It records how patients perform and how much support they need during their therapy sessions. Assessment tools evaluate the sensors and motors of the device during specific functions, where the results can be analyzed and documented to predict the patient’s state and therapy progress.

**ArmeoSpring**

This is an instrumented arm orthosis with a spring mechanism for adjustable arm weight support in a large 3D workspace that can be used as a real time input device to the associated therapy software Armeocontrol. The purpose of ArmeoSpring is to support functional therapy for patients who have lost the function of or have restricted function in their upper extremities caused by cerebral, neurogenic, spinal, muscular or bone-related disorders. The system is mounted on a mobile platform for easy transfer, weighs a maximum 82Kg and requires an operational space of 3 x 3 x 2 m (l x w x h)[18]

**ArmeoBoom**

This is a product specifically designed for upper extremity therapy in out-patient clinics and home settings. It combines self-directed movement exercises with augmented feedback and assessment tools driven by the associated therapy software Armeocontrol. The purpose of ArmeoBoom is to support functional therapy for patients who have lost the function of or have restricted function in their upper extremities similar to those mentioned with ArmeoPower and ArmeoSpring. The system is very light, weighing less than 20Kg and requires a minimum operational area of 2 x 2 x 2.3 m (l x w x h) [16].

![Figure 15: (left) ArmeoPower, (middle) ArmeoSpring, (right) ArmeoBoom.](image)

**Meal-Assistance Using HAL Robot Suit (HAL-UL)**

The HAL-UL was developed by Kawamoto et al [14], which attempts to bridge the gap between a purely upper arm and lower arm exoskeleton by providing wrist assistance. HAL-UL Exoskeleton aids patients with upper limb paralysis such as cerebrovascular disorder and cervical cord damage. It can achieve a range of free motion as shown in Figure 16, i.e. using a camera to detect food and generates reaching trajectories. A microphone is used to inform the system of which food the user wants. The HAL-UL assists and moves the disabled limb which prevents disuse syndromes and gives the user some flexibility and control over eating. Performing everyday tasks which also double up as rehabilitation improve the patients recovery, motivation and well being.

The human upper limb has 7 DOFs which matches the HAL-UL with 3 DOFs in the shoulder joint, 1 DOF in the elbow,3 DOFs in the wrist. This device is fixed to a chair
Figure 16: HAL Meal Assistance

since it is heavy. This would reduce its portability, unless fixed to a mobile wheel chair. Individual finger movement is not supported but does provide grip assistance.

**Pneumatic Upper Body Rehabilitation Exoskeleton.**

Tsagarakis and Caldwell developed a 7-DOF upper body rehabilitation exoskeleton using Pneumatic Muscle Actuators (pMA), shown in figure 17. Pneumatic muscles have an excellent power to weight ratio, which allows their entire exoskeleton to weigh less than 2Kg. The advantages of their system include low mass, excellent power to weight ratio with, inherent safety, natural compliance, ease of fabrication and low cost. This type of actuator has a displacement limit which provides safety to the user. The 7-DOF motion of the exoskeleton is similar to a human arm from the shoulder to the wrist. The exoskeleton is lightweight, low cost and comfortable. The exoskeletal arm is constructed for a typical adult, length changes can be adjusted if necessary, allowing multiple users [43].

Figure 17: Tsagarakis and Caldwell Upper body Exoskeletal

**ArmAssist**

As shown in figure 18, it is a project backed by a business initiative called FIK and developed by researchers from Spain. It is a portable robotic device for tele-rehabilitation. It is to help people with neuromuscular disabilities, such as stroke victims, to regain function. It consists of a mobile-base that is connected to the user through an orthotic that records and measures the movements of the shoulder and elbow. Arm movements are translated to movements in a video game, thus helping with rehabilitation of the upper limbs. The device can be used at home, while the doctor can monitor the performance
online through the quantitative results obtained from the games.

In order to monitor movements and forces exerted by the arm, the ArmAssist is equipped with two types of low-cost sensors, a 2-axis position and 1-axis force sensor [21]. In the majority of cases rehabilitation cannot be done outside the medical center due to the excessive size of current systems, which impede their portability. Moreover, the therapists have no control over the therapy and so cannot provide a suitable programme of monitoring and enhancement.

Using tele-rehabilitation software (which is included with this device), a link is created between the patient and the therapist, and enables training him or her in their homes. Independent rehabilitation can take place while using the computer programme with an internet connection, the doctor can ensure the patient is doing the exercises correctly [40]. The ArmAssist was designed to be affordable: the passive unit at 100 Euros and the active unit at 500 Euros. The simplicity of the device was attained by utilizing a simple design with minimal moving parts, and a simple product life cycle. The ArmAssist is highly portable and weighs less than 4 kg [21].

![Figure 18: ArmAssist Exoskeleton](image)

**Figure 18: ArmAssist Exoskeleton [40]**

![Figure 19: Myomo mPower 1000](image)

**Figure 19: Myomo mPower 1000[30]**

**Panasonic Powered Upper Arm Exoskeleton**

As shown in Figure 20, this device is developed by Matsushita Electric Industrial (parent of consumer electronics company Panasonic). It is a robotic suit designed to help recover upper limb movement of stroke patients who are paralyzed on one side of the body. The robotic suit includes sensors and rubber muscles controlled by compressed air. Sensors at the elbow and wrist allow a healthy arm to control the eight artificial
muscles.

When patients move their unaffected arm, sensors detect the movement and send signals to the rubber muscles that are wrapped around the impaired arm mirroring the movement of the unaffected arm. The rubber muscles are linked to a compressor unit with a display indicating the number of times the rubber muscles are moved [32]. The Exoskeleton weighs just 4-pounds[8].

Myomo mPower 1000

Myomo combines advances in robotics and neuroscience, with software applications and therapy protocols, to enable neurologically impaired individuals to increase movement in partially paralyzed arms with the aim of regaining functional capabilities. As shown in Figure 19, the system is a neuro-robotic arm brace that fits like a sleeve on a person’s arm. The arm brace has sensors that sit on the skin’s surface and detect even a very faint muscle signal. When a person with a weak or partially paralyzed arm tries to move their arm and a muscle signal fires, the robot in the mPower 1000 engage to assist in completing the desired movement. Myomo’s robotic arm brace was developed at MIT and has been clinically proven effective in patients from two days to 21 years after stroke. The system can be operated by the Bicep, Tricep or both. It has a range of motion from 3 to 130 degrees and weighs just 846g[30].

ARmin

It is a 4-DOF exoskeleton designed for neurological rehabilitation. As shown in Figure 21, the robot is fixed via an aluminum frame at the wall with the patient sitting beneath. The patient’s torso is fixed to the wheelchair with straps and bands. The exoskeleton moves the elbow and the wrist, whereas the shoulder joint is actuated by an end-effector connecting the upper arm with the wall mounted unit. There are 3 DOFs for shoulder and one for elbow, making up the four active DOF. A vertically oriented linear motion module (axis 1) performs vertical shoulder rotation (flexion/extension and abduction/adduction) movements.

Horizontal shoulder rotation (horizontal flexion/extension and abduction/adduction) is realized by a backlash free and back-drivable harmonic drive module attached to the slide of the linear motion module. Internal/external shoulder rotation is achieved by a special custom-made upper arm rotary module that is connected to the upper arm via an orthotic shell. Elbow flexion/extension is realized by a harmonic drive rotary module. The ARMin prototype is extended with two additional DOFs for the forearm to allow training of activities of daily living [27].
**BONES**

It is an upper arm exoskeleton (figure 22) mimics upper arm motion as a spherical joint rotating about the shoulder. The arm is actuated at the elbow by two rods that can passively slide. The rear end of each these rods is actuated by two pneumatic cylinders. The range of movement is close to human movement, except at the elbow, which is limit to prevent the robot from contacting the subject’s torso. The device can be adapted to a wide range of stroke patients. The arm length can be adjusted to accommodate 27.9 cm to 44.4 cm.

BONES targets patients with severe to moderate arm impairment. The upper arm exoskeleton weighs 3438g, the forearm exoskeleton module weighs 921g, totalling a combined weight of 4359g. An average human upper arm weighs approximately 2500g, and a human forearm approximately 1720g, for a total of 4220g. Thus, the mass of the exoskeletal parts that the subject has to move is comparable to the mass of a human arm. This relatively lightweight exoskeleton is made possible by the use of a parallel mechanism and mechanical grounded actuators. The total weight of the robot, including the mechanically grounded actuators, is 18.5kg [20].

**T-WREX**

The Therapy Wilmington Robotic Exoskeleton[3], more commonly known as T-WREX, is an antigravity arm orthosis designed to enable individuals with significant
arm weakness to achieve intense movement training without the expense of a supervis-
ing therapist. It is a passive, five degrees-of-freedom, body powered device that contains
no robotic actuators. It provides a large 3D workspace, enabling naturalistic movement
across approximately 66% of the normal workspace of the arm in the vertical plane and
72% in the horizontal plane. Elastic bands are placed on the exoskeleton to achieve
gravity-balance of the upper and lower arm at all positions in 3D space.

The structural design of T-WREX is based on the Wilmington Robotic Exoskeleton
(WREX). The WREX was created as an assistive device for children with neuromus-
cular weakness such as muscular dystrophy or arthrogryposis [41]. It is a functional
gravity-balanced upper limb orthosis that assists children with tasks such as eating and
writing. Position sensors are added to each joint, and a custom grip sensor was designed
for the hand, compact rotary potentiometers sensors provide the resolution of position
measurement of the endpoint of the orthosis within plus or minus 0.38 cm. The handgrip
contains a hydraulic bladder which detects pressures up to approximately 345 kN/m²,
with a resolution of about 2.0 kN/m², which is small enough to detect a very weak grasp
[38]. T-WREX’s brother, Pneu-WREX, is a pneumatic version of the rehabilitative robot
arm. TWREX is shown left and Pneu is shown right of figure 23

**Figure 23:** (left) T-WREX and (right) Pneumatic T-WREX

**CADEN-7**

CADEN-7 stands for cable-actuated dexterous exoskeleton for neuro-rehabilitation.
The device has 7 DOFs. Proximal placement of motors and distal placement of cable
pulley reductions were incorporated into the design, leading to low inertia, high stiffness
links, and back drivable transmissions with zero backlash. Various control interfaces
were examined, force impedance, were the user must apply force to a sensor to move the
exoskeleton, surface electromyography (sEMG) which monitors the electrical potential
during the muscle activation process.

**Java Therapy system**

It tracks a users arm movement through a variety of mice and joysticks. It was
initially focused on a low-cost commercial force feedback joystick (Logitech Wingman
Forcefeedback Pro). This joystick can apply up to 10N in order to resist or assist in
movement and can be programmed to implement a variety of force effects such as springs,
dampers, and constant forces. Several additions were required in order to make the
joystick usable for most individuals lacking hand grasp ability. For this reason additional
left and right-handed orthopedic splints were designed to clip on to the preexisting
handle. The splints connect securely with the joystick handle without using fasteners, and have straps that secure the joystick to the hand.

To support the weight of the arm, a commercially available articulating armrest is incorporated. Both the joystick and armrest can be secured to a support surface through the use of a custom designed base. The resulting system constrains the arm into a similar posture for each user, and allows comfortable movement of the hand in a 10cm by 10cm workspace in the horizontal plane. The primary joint motions used to move the joystick are shoulder internal/external rotation and shoulder and elbow flexion/extension. The total cost of the force feedback joystick configuration including armrest, splint and base is approximately US$240 [10]. This system is called “Java Therapy” because of its use of the Java programming language. Users log on to the system using the web, perform a customized program of therapeutic activities, and receive quantitative feedback of their rehabilitation progress. A remote supervising care giver can then monitor progress, make changes to the exercise program, and provide information and encouragement.
4.2 Lower Arm Exoskeletons

Lower arm Exoskeletons include exoskeletons supporting the wrist, hand and fingers. As shown in figure 3 in the introductory section, each consists of an Ellipsoidal joint for the wrist, hinge joints for the fingers and saddle joint for the thumb.

**Hand Exoskeleton**

Fleischer et al [7] performed a survey on 2 exoskeletal devices developed within their lab at the University of Berlin, Germany. These included a leg exoskeleton and a hand exoskeleton as shown in Figure 26. The exoskeleton hand has 16 actuated joints, 4 for each finger, and can be used in rehabilitation after surgery. Common control methods usually involve force sensors, however there are problems such as the natural delay as the brain tells our muscles to move and the actual contraction of the muscles. The exoskeleton hand was designed to support rehabilitation and diagnostics after hand surgery or stroke. All fingers can be used but does not include the thumb. EMG signals are used for diagnostics but not used for control, which uses joint and force sensors. In the hands rehabilitation mode, users can follow predefined trajectories set by physiotherapists. This allows repeatable exercise to be performed.

Since user’s force and environmental force cannot be distinguished from each other, the system is insufficient for grasping during rehabilitation. The restricted space on the exoskeleton prevents using additional sensors to detect the different internal and external forces. The greatest difficulty in using EMG to control hand movements is that not all the muscle that control the hand are found in the forearm, some are also in the hand. While the forearm consists of many tightly packed muscles which make it difficult to decipher which muscles are being used. Although predicting hand motion is possible, it is unlikely that every move can be perfectly replicated using EMG alone.[7]

**Hand Mentor**

The Hand Mentor is used to aid upper-extremity rehabilitation in a patient with chronic stroke with minimal finger and wrist movement, shown in Figure 27. It is focused on improving active range of motion (AROM) in wrist flexion and extension, wrist control, and initiating movement distally. It has three treatments with anti-spasticity modes of varying duration, two motor control modes, a motor unit recruitment mode which uses surface electromyography (EMG), while feedback is in the form of light-emitting diodes (LEDs).

The Hand Mentor operates with pneumatic muscles which will inflate and actively
assist the movement if the patient is unable to obtain the target position. This enables the user to practice everyday activities like sweeping the floor. The Hand Mentor is simple enough that it could be used in the home environment, which could further reduce patient need for direct therapist intervention [23].

Kutner et al. concluded in their paper using the Hand Mentor, that a Receipt of 30 hours of therapist-supervised repetitive task practice combined with 30 hours of robotic-assisted therapy during the subacute phase of stroke recovery resulted in patient-rated improvement in hand function similar to that observed with receipt of 60 hours of therapist-supervised repetitive task practice [31].

**Master hand NESS H200**

As shown in Figure 28, the Ness H200 is an innovative tool developed in the Netherlands by Bioness, which currently supply the Dutch market. It is an advanced rehabilitation tool based on Functional Electrical Stimulation (FES) for the hand and forearm to train and perform functions in the central nervous system of with spinal cord injury. The NESS H200 is a reinforced orthosis (splint) with electrodes integrated into the orthosis near the affected muscles. Muscle stimulation from the electrodes aids in movement of the effect limb [2]. There are also similar alternatives of FES incorporated technology:
The Bionic Glove (marketed as Tetron Glove by Neuromotion, Edmonton, Canada), The Fesmate (NEC Medical Systems, Tokyo, Japan), the Freehand system (NeuroControl, Cleveland, USA)[12].

**The Hand Wrist Assistive Rehabilitation Device (‘HWARD’)**

It is a 3-DOF, pneumatically actuated device that assists the hand in grasp and in release movements [9]. HWARD forms 3 groups, one for 4 fingers, one for the thumb and one for the wrist. The hand is secured to the robot mechanism via three soft straps, and the forearm is secured inside a padded splint that is mounted to the surface of a platform. Joint angle sensors in the robot are used to measure the movement of the robot’s joints, and hence movement of the subject’s limbs when attached to the robot. This allows real-time virtual reality hand movements.

The HWARD, as shown in Figure 29, can assist grasping and releasing movements while simultaneously allowing the subject to feel real objects during therapy. It provides assistance which combines wrist extension with hand grasping (known as a “power grip”), and wrist flexion with hand release. HWARD allows the movement of 4 fingers as a single unit about the metacarpophalangeal (MCP) joint with a range of movement (ROM) of approximately 25 to 90 degrees flexion. the system allows thumb movement out of the plane of the palm and fingers with an approximate ROM of 90% full extension to 75% of full flexion. Finally, HWARD allows wrist flexion-extension movement with a ROM of approximately 20 degrees extension to 15 degrees flexion [6].

The device was specifically designed to be back driveable so that subjects can move the mechanism while it is in a passive state. Back driveable robots will not encumber the subject’s natural movement even while applying assistive forces. In addition, they can be used as tools for assessing kinematic measures of movement performance such as active range of motion. Back driveability is achieved by minimizing friction in the mechanism. HWARD is pneumatically actuated, with rotary potentiometers measuring finger, wrist, and thumb joint angles.

![Figure 29: The Hand Wrist Assistive Rehabilitation Device (‘HWARD’)](image)

**Orthostic Pinch Exoskeleton**

DiCicco et al. created an orthostic pinch exoskeleton for the hand that aids the user in pinching, which can be adjusted for many users. Pneumatic pistons control the system, while movement of the joints is produced by cables running along the front of each finger band, and through to the backside of the hand. A floating link mounted between the finger band closes to the base plate, which is connected to a second pneumatic actuator for further movement. [28] The pinching exoskeleton can be seen in figure 30.
4.3 Mechanical Rehabilitative Exoskeletons

Mechanical Rehabilitative Exoskeletons are an alternative to their power brethren, and provide a similar level of rehabilitation. They function well with patients that still have strength but are lacking control.

Saebo provides a range of mechanical exoskeletal devices shown in figure 31. Information on these products was gathered from the Saebo webpage[37]. The SaeboFlex, supports a weakened wrist, hand and fingers. It postings the wrist and fingers into extension in preparation for functional activities. The user then has to grasp their hand to close on a object, the extension spring attached to the orthoses assists in re-opening the hand to release the object.

The SaeboStretch is a dynamic hand splint, which helps to prevent joint damage while improving and maintaining range of motion. It provides maximum positioning by utilizing a dynamic hand piece that comes in three varying grades of resistance to better match patient’s specific needs. The SaeboReach not only incorporates the affected wrist and hand but also the elbow. It is ideal for neurologically impaired individuals that have hand and elbow involvement. The SaeboMAS dynamic mobile arm support system is a zero gravity upper extremity device specifically designed to facilitate and challenge the weakened shoulder and elbow during functional tasks and exercise drills.
5 Discussion

As Hesse et al. [39] mentioned in their review of Upper and lower Extremities, rehabilitant robots are meant to be an adjunctive tool to increase the intensity of therapy. Currently a robot cannot replace the multi-level interaction between patients and therapists. A friendly face that can motivate patients during therapy, which is not provided by robotic rehabilitation. However, a physiotherapist can earn anywhere from £20,000 to £50,000. Balancing the cost and services of a rehabilitation exoskeleton against a physiotherapist can play an essential part in making a hospital cost efficient.

Manipulative physiotherapy procedures are labor intensive with hundreds of arm movements per day. Manipulation requires high levels of one to one attention from highly skilled medical personnel, this is an issue because of the shortage of physiotherapists. The need for longer treatment periods, more intensive regimes and the shortage of staff mean that robotic and power assisted techniques are increasingly viewed as a potential replacement. There has been a lot of work on power assisted devices, hence there is a increasingly diverse selection. However, this is the opposite for portable exoskeletal devices which are rare. [19]

The robotic devices such as the MIT-MANUS and MIME have a strong background in rehabilitative technology, and have been proven to be effective in aiding recovery. These robots are widely accepted but all devices have similar operations and designs, hence any future designs are unlikely to change significantly. The trend seems to be moving towards more portable and low cost technology, such as the Upper Extremity Motor Function Rehabilitation And Assessment System. In terms of exoskeletons, similar trends have been noticed. Originally exoskeletons weight and power constraints forced the systems to be fixed, however new technology creating ultra strong and yet light weight materials, creation of alternative actuators, and miniature yet power efficient electronics allowed for exoskeletons to become more portable.

An exoskeleton does not replace your muscles but simply augments them. Users are still required keeping active, walk outside, go shopping and preforming other daily tasks. There is much potential in abusing these devices to make everyday living easier, potentially causing muscle dystrophy. For long term users, the exoskeleton should double up as an exercise machine providing a resistant mode to improve strength. Intelligent software may be required to reduce the over reliance of such technology.

A great importance for rehabilitative devices is determining a correct set of predefined motions, Marchal-Crespo and Reinkensmeyer in their review on control strategies for robotic movement training after neurologic injury[26] provide references from over 20 papers on detraining normative trajectories from mathematical models of normative trajectories such as a minimum-jerk trajectories, pre-recorded trajectories from unimpaired volunteers, pre-recorded trajectories during therapist-guided assistance and desired trajectory on the movement of the patients ”good” limb. Some robotic therapy controllers do not require desired trajectories. For example resistive strategies can be implemented without desired trajectories. EMG-proportional controllers do not require desired trajectories since the participant’s self-selected EMG specifies the desired movement.

To design an effective exoskeleton requires research into human kinematics and dynamics of everyday living situations. Perry et al recorded 19 daily activities using a Vicon motion capturing system and where able to design their exoskeleton ROM to allow these motions to be preformed. Most of the upper body rehabilitative robots have been designed to train the shoulder and elbow, and support the limb as needed. The limb is then moved either passively or actively. Far fewer robots have been designed to train the arm and wrist or even the arm and hand together.
For a system to be easy to use, it should be intuitive and clearly understandable without explanation. It should allow simple one-handed donning and doffing. Considering the use of a virtual environment, mappings between actual and on-screen motions that are not readily intuitive should be avoided [21]. In addition to rehabilitational devices, monitoring of patient welfare is just as important, and with exoskeletons it would beneficial to the user to have vital signs recorded. In which case the use of smart wearable technology that can be incorporated into clothing [25] would be useful. Exoskeletons can use a haptic interface to control the exoskeleton. However haptic feedback would also be beneficial to the user, allowing the user to feel what they touch if their fingers are covered.

Protheses, exoskeletons, robotic hands, all contribute to a better standard of living, loosing a limb no longer becomes such a disabling disability, the functions you have lost can be returned, the feelings given back, but most importantly the normality of life can be returned. This better standard of living is keeping us healthier longer, 60 is the new 50 and 50 is the new 40 but there is no running away from old age, population projections suggest the number of centenarians in the UK will reach almost 80,000 by mid-2033, old age can reduce our strength making it difficult to grip and hold heavy objects, it causes us to miss some of our every day enjoyments that we take for granted, like walking, exhaustion and fatigue cause us to eventually stop enjoying them, robotic exoskeletons can restore mobility returning back independence to the user, exercise is important to sustaining a healthy body and mind. Exoskeletons are a way to do this.

6 Conclusion

Exoskeletal devices that can be worn in a patients every day life and still provide rehabilitative properties are the future of medical heath care, alleviating the pressure on the physiotherapists shortages allowing for a better allocation of resources. Currently there are 2 major complexities of upper body exoskeletons that limit their abilities. One is the complexity of the hand i.e. the amount of actuators and control strategies make function difficult to replicate within the confines of a small and light weight package. The 2nd one is the transfer of weight of the exoskeleton to the ground, if you cannot transfer the weight, then the weight has to be borne on the wearer, which is unacceptable for the disabled. Ideally a portable exoskeleton that allows a user to preform daily tasks while at the same time performing therapy would be very beneficial to a user. To achieve reasonable performance the weight would need to be displaced to the ground. This is why either a full body exoskeleton is required or a minimal load bearing leg or legs be incorporated. By incorporating Exoskeletal appendages into hospital re reduces the reliance on health care.

Often what lacks in rehabilitative robots and exoskeletons is aesthetics, and the vast majority of current devices are still the bare bone mechanical machines. Although aesthetics plays no role in determining how useful the robots are, it can make the patient more relaxed and happy to use the device. Making the user more comfortable with the machine quicker. The rehabilitative robots and exoskeletons described in this review are only some of the available systems. The aim is to provide a good overview to analyze where rehabilitation robotics is heading. Exoskeletons are expected to play an important role in future physical and occupational therapy as they provide an easy, consistent and maintainable interaction with real and virtual environments, allowing patients to use a multitude of multimedia devices. As we see power systems become more efficient we should see more wearable technologies such as exoskeletons appearing.
References


