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# Literature Review

## Introduction

The likelihood of having a Stroke increases with age. Statistics show that the population of the UK is aging, due in part to an increase in life expectancy. This means that Stroke is becoming more prevalent in the UK. The increase in Stroke prevalence places a large burden on the NHS and rehabilitation services, especially considering that it is understood that effective neural rehabilitation should be intensive and occur early after the onset of Stroke. In order to ease the burden on medical services and provide more access to therapy, research is increasingly focused on the use of robotics.

## Stroke Mechanisms and Effects

Stroke, also known as Cerebrovascular Accident, is the leading cause of disability in the UK according to the Stroke Association (2018). Stroke is classified by 2 mechanisms: Haemorrhagic Stroke and Ischaemic Stroke. Haemorrhagic Stroke occurs when an artery in the brain ruptures, often as a result of high blood pressure. Ischaemic Stroke occurs due to the blockage of an artery in the brain, usually caused by a blood clot or fatty deposits. Both mechanisms lead to cell damage or cell death in the affected region of the brain because of a lack of oxygen (Moskowitz et al, 2010).

The symptoms of Stroke are wide ranging and dependant on which region of the brain has been affected and the severity of the Stroke. Different regions of the brain control different behaviour, as shown by figure 1.2.1:

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|  |
| Figure 1.2.1: Different regions of the brain associated with control of different behaviour (Stroke Association, 2018) |

Common symptoms include motor impairment along one side of the body (known as hemiplegia), impairment to speech, difficulties swallowing and impairment to memory. It was found in a study by Sommerfeld et al (2004) that up to 80% of Stroke patients initially experience motor difficulties. Lawrence et al (2001) performed a community-based study on first-time Stroke patients in which 77.4% of the Stroke patients suffered from upper limb impairment.

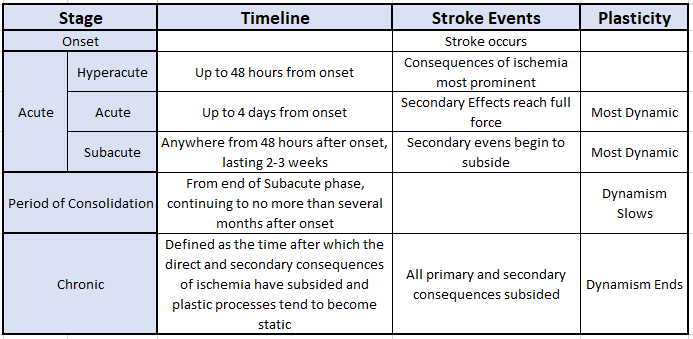
Stroke has a significant negative impact on a patient’s quality of life. Regular activities such as walking, eating, and manipulating objects become difficult or impossible. This often leads to dependency on care and assistance from others. Aside from the personal impact on the patient, Stroke has financial implications for society. Xu et al (2018) estimated the mean cost of health and social care per Stroke patient to be £46039. This figure is in close agreement with the Stroke Association (2017), who estimated that in 2015 the mean cost of health and social care per Stroke patient was £45409.

## Stroke Recovery

### Neural Recovery

Since Stroke is a neurological issue, it follows that Stroke recovery must exploit neurological mechanisms. Cerebral plasticity (otherwise known as neurofunctional plasticity) is the ability of the brain to “reorganise during ontogeny, learning or following damage” (Duffau, 2006). It is this ability of the brain to reorganise that provides the mechanism for Stroke recovery, though this is not yet fully understood according to Kreisel et al (2007).

Without the intervention of rehabilitation, there does remain some natural motor recovery after Stroke. The timeline for natural motor recovery after Stroke is summarised in the table 1.3.1:



It can be seen from table 1.3.1 that the neurofunctional plasticity of the brain is most dynamic after the Hyperacute phase, but then the dynamism slows. Once the patient has reached the Chronic stage, the plastic processes become static and motor deficits remain unchanged after this point (Kreisel et al, 2007).

### Physiotherapy

The use of physiotherapy is an accepted element for the rehabilitation of Stroke patients. Physiotherapy is applied by trained physiotherapists, though there has been a rise in the use of robots for post-Stroke physiotherapy in recent years. There is little agreement on the effectiveness of different rehabilitation strategies. 2 main rehabilitation strategies are in widespread use according to Morreale et al (2016) and Coleman et al (2017). Proprioceptive Neuromuscular Facilitation (PNF) involves stretching and contracting a targeted muscle group, as shown by figure 1.3.2.1:

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| Figure 1.3.2.1: Proprioceptive Neuromuscular Facilitation (PNF) (Marek et al, 2005) |

More advanced PNF involves resisting the movement of the patient, although this relies on the patient having enough motor control to move the exercised limb.

Cognitive Therapeutic Exercise (CTE) involves high level cognitive training through task-based activity (Lee et al, 2015). Robotic rehabilitation devices use the CTE strategy due to the ease of integrating tasks using computer game or virtual reality technologies.

Van Peppen et al (2004) performed a systematic review which showed that physical rehabilitation is more effective when performed intensively and early after Stroke. This is corroborated by Morreale et al (2016), who observed that early intervention was a factor on the effectiveness of rehabilitation. Indeed, these findings make sense when considering the neurofunctional plasticity of the brain is most dynamic early after onset, as shown in table 1.3.1. Morreale et al (2016) also stated, however, that “the optimal schedule and content of rehabilitation in the acute phase of care is still undefined”. It is generally agreed that early intervention of physical rehabilitation is important for recovery, but there is little evidence to support the existence of an optimal rehabilitation strategy. Kreisel et al (2007) agree, stating that “mechanisms that support or modulate recovery are not yet fully understood”.

## Stroke Prevalence

A study by O’Mahony et al (1999) found that 1.75% of a sample population of 2000 had suffered from Stroke. Stroke can occur in people of any age, but it is shown by the Stroke Association (2018) that the likelihood of an individual having a Stroke increases with age. According to the Office of National Statistics (2018) the population of the UK is aging, with 26.5% of the population projected to be aged 65 or older by 2041, as shown by figure 1.4.1:

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| Figure 1.4.1: Aging population in the UK (Office of National Statistics, 2018) |

This ‘greying’ of the population is common across most Western societies due to falling birth-rates and an increased life expectancy, and is expected to become an issue globally. Figure 1.4.2 shows an age group distribution of the population using data gathered from 195 United Nations countries from 1950 onwards and projected to 2050:

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| Figure 1.4.2: Projected aging of a worldwide population (Lee and Mason, 2011) |

Observing the projected trend, it is reasonable to expect that the total number of Strokes will increase. This will increase the demand and financial costs upon the NHS and rehabilitation services, especially when considering that the research shows that early and intensive physical rehabilitation is an important factor in recovery.

## Using Robots for Rehabilitation of Stroke Patients

In recent years there has been an increase in interest and research into the use of robots for rehabilitation of Stroke patients. This is mainly because of the increased demand upon medical and rehabilitation services due the greying of the population identified in section 1.4. According to Maciejasz et el (2014) and Culmer (2007), rehabilitation robots are categorised by their mechanical structure as either an end-effector based device or an exo-skeleton based device. These can be further categorised as class 1 or class 2 devices, as stated by SOURCES. Class 1 devices are of high cost and intended for lab use, whereas Class 2 devices are low cost and intended for home use. Most of the research in robotic rehabilitation devices has focused on Class 1 devices, since it was necessary to produce evidence that robotic rehabilitation was a valid rehabilitation strategy.

DESIGN PARAMETERS

Control Hierarchy

### Trajectory Generation

As with any robot designed to move an end-effector from a starting position to a desired position, a trajectory must be generated. A number of approaches exist, the selection of which depends on what the trajectory is required to optimise. The simplest solution is to generate a simple linear trajectory which covers the shortest distance between the current position and the desired position. This method, however, potentially means that unacceptable changes in acceleration may be planned.

A better solution, implemented by the MIT-MANUS (Hogan et el, 1998), produces a minimum jerk trajectory. A minimum jerk trajectory minimises jerk, which is the third time derivative of position (or first time derivative of acceleration), thus a minimum jerk trajectory ensures that there should be no unacceptable changes in acceleration.

### High Level Control Strategies

All rehabilitation robotic devices must consider and implement both high-level control strategies and low-level control algorithms according to both Maciejasz et al (2014), who performed a systematic review of rehabilitation robotic devices, and Marchal-Crespo and Reinkensmeyer (2009), who performed a systematic review of control strategies for rehabilitation robotic devices. The high-level control strategy describes the movement strategy of the robot designed to promote neurofunctional plasticity of the damaged motor control areas of the brain, whereas the low-level control algorithms describe the specific implementation of position, force, impedance or admittance control. Erol and Sarkar (2007) suggest that the role of the high-level controller is equivalent to the role of the physiotherapist, in that it monitors the status of the task, monitors the safety of the patient and “informs the low-level controller about the task updates”.

High-level control strategies can be broadly split into four categories: 1. Assistive control, 2. Challenge based control, 3. Haptic stimulation, and 4. Non-contacting coaching (Maciejasz et al, 2014) and (Marchal-Crespo and Reinkensmeyer, 2009).

Assistive control is a strategy whereby the patient is aided to complete the task. Usually, measures are put into place to allow the patient to move unrestricted as long as the correct trajectory is being followed. If there is deviation from the desired trajectory a restoring force proportional to the level of deviation is applied, as seen with the MIT-MANUS (Krebs et al, 2004). An Assistive control strategy is commonly implemented with Impedance or Admittance control as the low-level control algorithm.

Another type of Assistive control uses a counterbalance to make a task easier for the patient, the Wilmington Robotic Exoskeleton (WREX) (Sanchez et al, 2005) being a good example. A further method of implementing Assistive control is to use Surface Electromyography (sEMG) sensors to measure signals in the nerves, which is used to trigger assistance according to the patient’s movement intention. This is difficult, however, since the noise to signal ratio is very high.

Challenge based control methods are designed to make the task more difficult for the patient, and are categorised as resistive, error amplifying or constraint induced. Resistive strategies resist the movement of the patient, simulating the more advanced techniques of Proprioceptive Neuromuscular Facilitation (PNF). Error amplifying strategies amplify movement errors rather than decrease them, according to (Marchal-Crespo and Reinkensmeyer, 2009). Error amplification strategies have been shown to increase motor learning compared with assistive strategies according to Patton et al (2006), who tested 18 hemiparetic Stroke patients.

Constraint induced strategies involve constraining the unimpaired limb, so that the impaired limb must perform the task. This particular strategy is particularly suited to exercises involving 2 limbs, for example reaching for a sizable object. Constraint induced strategies are not relevant, however, for end effector type devices such as the MIT-MANUS or hCAAR. In general, challenge based control methods are not useful for severely impaired patients with little or no motor control, since the patient does not have sufficient control to begin the required movement.

Haptic strategies involve the use of Virtual Reality (VR) or Altered Reality (AR), where the user must where a headpiece which provides visual feedback in a 3-Dimensional environment. This was implemented by Montagne et el (2007), who found that the use of an engaging VR environment for visual feedback coupled with an exoskeleton robotic rehabilitation device significantly increased patient motivation. A clinical trial of this device showed increased motor control after 6 weeks of use, though only 3 chronic patients were tested and there is no evidence to show that the implementation of VR provides a greater clinical benefit than simply displaying visual feedback via a computer screen, as implemented by many other robotic rehabilitation devices.  
 Non-contact coaching devices do not interact with the patient, and simply provide instructions to the patient, according to both Maciejasz et al (2014) and Marchal-Crespo and Reinkensmeyer (2009). This may be useful for patients with high amounts of motor control but is not useful for patients with higher levels of disability who require assistance to complete exercises.

### Accounting for Interaction Forces

The case of a robotic physiotherapy device interacting with a human patient should be considered as a coupled mechanical system (Maciejasz et al, 2014). This means that the use of a force control strategy or a position control strategy alone is insufficient, since interaction forces with the patient are not accounted for and are thus inherently unsafe. Further to this, failure to account for interaction forces raises the possibility of controller instability. Hogan and Buerger (2004) demonstrated this instability by showing that the Rough-Hurwitz stability criterion were met when considering an example system in isolation but were not met when considering the same system in a coupled mechanism.

In order to account for interaction forces, the majority of rehabilitation robotic devices use Impedance Control or Admittance Control as the low-level control strategy. Impedance Control and Admittance Control involve modulating the dynamic behaviour of the robot alongside position or force control, according to Hogan (1984), by specifying the robot’s position and force relationship using virtual mass, spring and damping characteristics which are heuristically determined (Richardson, 2001). Richardson (2001) explains this using figure 1.5.3.1:

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| Figure 1.5.3.1: The external force changing the desired position (Richardson, 2001) |

Essentially, the desired position changes due to the application of an external force in a predictable manner defined by the mass, spring and damping characteristics.

A physical system which accepts force inputs and produces position outputs is defined as an admittance. A physical system which accepts position inputs and produces force outputs is defined as an impedance (Ott et al, 2010) (Hogan,1984). The end effector of a mechanically coupled robot is subject to physical constraints, so it acts as either an admittance or an impedance. If the environment acts as an admittance, the end effector must act as an impedance according to Hogan (1984). Conversely, if the environment acts as an impedance, the end effector must act as an admittance.

### Admittance Control

Admittance control is a strategy whereby the force exerted on the end effector is measured, and the robot provides the corresponding displacement (Maciejasz et el, 2014). This means that the controller is acting as an admittance and the environment is acting as an impedance. As such, an Admittance control strategy is based around an inner loop position controller, as shown by the block diagram in figure 1.5.4.1:

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| Figure 1.5.4.1: A block diagram for a generic Admittance Controller (Richardson, 2001) |

According to Culmer et al (2010), the control signal can be simply defined as shown by equation number:

|  |  |
| --- | --- |
|  | Eqn number |

Where:

### Impedance Control

Impedance control is a strategy whereby the motion of the end effector is measured, and the robot provides the corresponding force-feedback (Maciejasz et el, 2014). This means that the controller is acting as an impedance and the environment is acting as an admittance. An Impedance control strategy is based around an inner loop force controller, as shown by the block diagram in figure 1.5.5.1:

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| --- |
|  |
| Figure 1.5.5.1: A block diagram for a generic Impedance Controller (Richardson, 2001) |

According to Culmer et al (2010), the control signal can be simply defined as shown by equation number:

|  |  |
| --- | --- |
|  | Eqn number |

Where:

### Selecting Impedance Control or Admittance Control

It is agreed by A LOT OF PEOPLE [13] that the advantages and disadvantages of Impedance and Admittance control systems are opposite, which makes sense considering that the definition of a mechanical Impedance is opposite to the definition of a mechanical Admittance.

When to select which controller?

## Rehabilitation Robots

Over the last 30 years, much work has been done in the area of rehabilitation robotics. In this section of the Literature Review there follows a brief overview of a selection of devices designed for upper limb rehabilitation of Stroke patients.

### MIT-MANUS

MIT-MANUS was the first robotic device designed for the rehabilitation of upper limbs of Stroke patients. The device consists of a direct-drive five bar-linkage SCARA (Selective Compliance Assembly Robot Arm) which provides 2 DoF movement for the elbow and forearm in the horizontal plane (Krebs et al, 2004). MIT-MANUS guides the patient’s arm through a series of predetermined exercises, with visual feedback provided on a computer screen according to Hogan et al (1995).

A series of extension devices were designed to aid in rehabilitation, since trials of MIT-MANUS found that positive motor learning effects on the exercised muscle groups did not have any effect on unexercised muscle groups. The first module extends the operating range of the MIT-MANUS by adding a third degree of freedom, which allow exercises to be performed in 3D space (Krebs et al, 2004). The second module was designed to rehabilitate the muscle groups in the hand. The MIT-MANUS and the hand module were successful enough that commercial products were released as the InMOTION Arm™ and the InMOTION Hand™. Figure 1.6.1.1 shows the InMOTION Arm™:

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| Figure 1.6.1.1: The InMOTION Arm™ |

According to Krebs et al (2004), one of the driving design features for the MIT-MANUS is that it is “configured for safe, stable, and compliant operation in close physical contact with humans”. This was achieved using Impedance Control as the low-level control strategy and ensuring that the hardware was backdrivable enough that frail patients could easily move the device. The Control hierarchy, which is similar that that seen across all robotic rehabilitation devices and defined in section 1.5, is shown by figure 1.6.1.2:

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|  |
| Figure 1.6.1.2: The Control hierarchy for MIT-MANUS (Hogan et el, 1998) |

The hierarchy in figure 1.6.1.2 shows the following process:

1. A high-level controller sets the sequence of targets for the therapy session.
2. The Task encoder translates the sequence of targets into sets of minimum-jerk trajectories.
3. The low-level controller is an impedance control strategy which uses the trajectories to provide varying assistance levels to the patient and control the interaction forces.
4. Force and position feedback from the hardware and environment are used as feedback parameters.

MIT-MANUS is the most extensively tested device for upper limb rehabilitation of Stroke patients. An initial pilot study was performed in which half of a cohort of 20 patients, as the control group, received only physiotherapist guided therapy and the second half of the cohort, as the experimental group, received physiotherapist guided therapy alongside robot guided therapy. The results of the pilot trial showed that the patients who received robot led therapy alongside physiotherapist led therapy gained significant motor control in the targeted muscle groups (Krebs et al, 1998). Importantly, it was also found that patients in the experimental group improved “further and faster” than those in the control group (Krebs et al, 1998). A further study retested a subset of the patients 3 years after the initial therapy, and it was found that the experimental group “showed further significant decreases in impairment measures of the affected limb” (Volpe et al, 1999).

### MEMOS

The Mechatronic System for Motor Recovery After Stroke (MEMOS) is a 2DoF planar robotic rehabilitation system designed to be as low cost as possible. This was achieved by building the device using as many ‘off the shelf’ parts as possible and ensuring that any part which could not be simply bought was able to be manufactured as simply as possible (Micera et al, 2005). Much like the MIT-MANUS, the MEMOS system guides the patient’s arm through a series of exercises with visual feedback provided on a computer screen.

The result of these cost saving measures is that the device costs only 4450 Euros. This is considerably more cost effective compared with the estimated $110 000 for the InMOTION Arm™, which is also a 2DoF planar robot. The MEMOS system consists of a handle connected to a trolley which runs on rails in a cartesian configuration, shown by figure 1.6.2.1:

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| C:\Users\adamg\AppData\Local\Microsoft\Windows\INetCache\Content.MSO\632B11EB.tmp |
| Figure 1.6.2.1: The MEMOS system (Micera et al, 2005) |

The MEMOS system defines 3 High-level control strategies: Completely assisted movement where the patient provides no input, assisted movement where the patient provides some input, and unassisted movement where the patient provides total input. If the patient fails to produce a minimum force after a certain amount of time, the robot moves the handle to the target with a predefined velocity. This is clearly seen in the control signal shown by equation number (Micera et al, 2005):

|  |  |
| --- | --- |
|  | Eqn number |

Where:

It can be seen from the control signal that the low-level control strategy implemented is Admittance Control, although this choice is not explained.

MEDICAL TRIALS

### MIME

Placeholder

MEDICAL TRIALS

### ARM-Guide

Placeholder

### EEULRebot System (lit review 52)

Placeholder

### The intelligent Pneumatic Arm Movement (iPAM) System

The intelligent Pneumatic Arm Movement (iPAM) is a cooperative dual robot system designed for upper limb rehabilitation of Stroke patients. Each of the dual iPAM robots uses pneumatic actuators to power the movement of its 3 joints (Culmer et al, 2005). Similar to other rehabilitation robotic devices, iPAM guides the patient’s arm through a series of exercises with visual feedback provided on a computer screen. The iPAM dual robot system is shown by figure 1.6.6.1:

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|  |
| Figure 1.6.6.1: The iPAM system (Jackson et al, 2007) |

As a high-level control strategy, the iPAM assists the patient to move towards the target. The iPAM can be adjusted to provide increased or decreased assistance. The input trajectory fed to the low-level control scheme is based on the kinematics of the arm. This procedure is consistent with the control hierarchy defined in section 1.5.

The iPAM uses Admittance control for the low-level control strategy. The control scheme is cooperative, since both robots must act in unison (Culmer et al, 2006). Admittance control was chosen because it favours pneumatic actuation, as agreed by Culmer (2010) and Richardson (2001). This is because it is difficult to model the non-linear dynamic effects, such as stiction, of pneumatic actuators accurately enough to ensure the accurate force control inner loop required for impedance control. The level of assistance provided to the patient can be changed by altering the stiffness coefficient in the admittance filter.

Initial trials demonstrate that the iPAM is capable of providing assistance to the upper limb with similar trajectories and patterns of movement to a subject’s unconstrained motion with no robot attached (Jackson et al, 2007). This was considered important because the system was designed not to exert unwanted and uncontrolled forces on the limb, which would encourage unnatural motions.

Ask andy/ pete about actual medical trials.

### hCAAR (home-based Computer Aided Arm Rehabilitation) System

The hCAAR (home-based Computer Aided Arm Rehabilitation) system is a 2DoF planar device developed to be installed in the houses of Stroke patients for upper limb rehabilitation. This would increase patient therapy hours, since literature suggests that the more access to therapy a patient has, the greater the potential for motor recovery. The hCAAR system guides the patient’s arm through a series of games, with visual feedback provided on a computer screen, as shown by figure 1.6.7.1:

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| Figure 1.6.7.1: The hCAAR system (Sivan et al, 2014) |

Since the hCAAR was intended for home use, it was designed to be as cost effective as possible. To this end, the first iteration of hCAAR used only position control to limit the use of expensive sensors. The second iteration of the hCAAR system uses a novel form of Impedance Control as the low-level control strategy whereby the motor current draw at each joint motor are estimated from a system model, allowing an inner loop which controls motor current draw rather than directly controlling torque, according to Firouzy (2011). This means that expensive torque sensors are not required for the force feedback necessary for an inner force control loop. The downside to this is that current measurements are noisy and thus the reliability of the control system is questionable. The block diagram for this arrangement is shown by figure 1.6.7.2:

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| Figure 1.6.7.2: The hCAAR system block diagram (Firouzy, 2011). |

Control equation and explanation.

The hCAAR has 2 distinct operation modes, which can be considered as the high-level control strategies. The first mode is assistive where a level of assistance, which can be varied, aids the patient to complete the tasks. The second mode is passive where no assistance is provided, which is used to collect data about patient progress.

The first iteration of the hCAAR system, which used position control only, was subjected to clinical trials with 19 patients, 17 of which completed the trial. Each patient had a hCAAR device installed in their home for a period of 8 weeks in order to undertake home exercises alongside their usual rehabilitation. A baseline assessment was carried out just before home installation, an assessment was carried out after the 8-week trial period and a further assessment was carried out after another 4 weeks (at the 12-week period). According to Sivan et al (2014), “statistically significant improvements were observed”, though it was noted that a study “comparing the combination of conventional therapy and hCAAR with conventional therapy alone needs to be explored”. It should be noted also that with position control only there is no mechanism for measuring or controlling the interaction forces with the patient, and thus dangerous torques or forces could be present.

### RUPERT (Robotic assisted Upper Extremity Repetitive Therapy) System

The Robotic assisted Upper Extremity Repetitive Therapy (RUPERT) device is an exoskeleton robot designed to rehabilitate Stroke patients suffering from upper limb mobility problems. The RUPERT device is aimed specifically at training 3DoF reaching tasks critical for daily living (Sugar et al, 2007). Assistance is provided to the patient through the use of pneumatic ‘air muscles’, much like the iPAM in section 1.6.6. The RUPERT system is shown in figure 1.6.8.1:

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| Figure 1.6.8.1: The RUPERT system (Sugar et al, 2007). |

Common to many robotic rehabilitation devices, as a high-level control strategy the patient is requested to make a movement. If after a certain amount of time the patient has been unable to do so, RUPERT provides assistance. Interestingly, the low-level control of the RUPERT device relies is open loop feedforward control. This means that the physiotherapist must set and monitor speed and position parameters in order to ensure patient safety, along with a set limit on the maximum angular speed of the joints. Sugar et al (2007) acknowledge this by stating that closed loop feedback control would be required when dealing with more severely impaired patients.

The second iteration of the RUPERT device was subjected to limited medical trials containing 10 Stroke patients who had moderate or mild upper limb motor control difficulties. The test ran for 3 weeks, with a modified Wolf Motor Test. Though the testing description is limited, 6 of the 10 test subjects completed the trials and 5 of these showed improvements in motor control in the targeted muscle groups.

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