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# Literature Review

## 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 1.1.1:

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| Figure 1.1.1: 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.

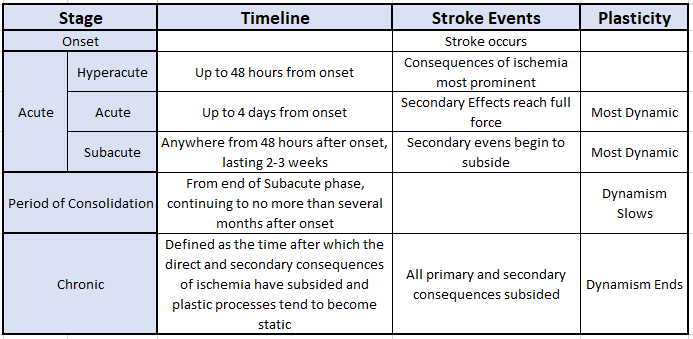
Stroke has a significant negative impact on a patient’s quality of life. Regular activities such as walking, eating, and manipulating objects become difficult or impossible. This often leads to dependency on care and assistance from others. Aside from the personal impact on the patient, Stroke has financial 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 1.2.1:



It can be seen from table 1.2.1 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 traditionally 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 1.2.2.1:

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|  |
| Figure 1.2.2.1: Proprioceptive Neuromuscular Facilitation (PNF) (Marek et al, 2005) |

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 and the difficulty of regulating contact forces in a meaningful way.

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 1.2.1. 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

PREVIOUS STATS

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 1.3.1:

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|  |
| Figure 1.3.1: 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.

Observing the projected trend, it is reasonable to expect that the total number of Strokes will increase. This will, of course, increase the demand and financial costs upon the NHS and rehabilitation services. The anticipated increase in demand upon rehabilitation services compounds with the research showing that early and intensive physical rehabilitation is an important factor in recovery. It is reasonable to state that the demand will far exceed the supply.

## 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 1.3. 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.

DESIGN PARAMETERS

Control Hierarchy

### 1.4.1 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 a number of factors.

Shortest Distance.

Minimum Jerk.

### 1.4.2 High Level Control Strategies

### 1.4.3 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 el, 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 1.4.3.1:

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| Figure 1.4.3.1: 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.

### 1.4.4 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 1.4.4.1:

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| Figure 1.4.4.1: 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:

### 1.4.5 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 1.4.5.1:

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| --- |
|  |
| Figure 1.4.5.1: 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:

### 1.4.6 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.

### 1.5.1 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 1.5.1.1 shows the InMOTION Arm™:

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| Figure 1.5.1.1: 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 1.4, is shown by figure 1.5.1.2:

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| Figure 1.5.1.2: The Control hierarchy for MIT-MANUS (Hogan et el, 1998) |

The hierarchy in figure 1.5.1.2 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.

MEDICAL TRIALS

MIT-MANUS is the most extensively tested device for upper limb rehabilitation of Stroke patients.

### 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 1.5.2.1:

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| --- |
| C:\Users\adamg\AppData\Local\Microsoft\Windows\INetCache\Content.MSO\632B11EB.tmp |
| Figure 1.5.2.1: 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

MEDICAL TRIALS

### ARM-Guide

Placeholder

### EEULRebot System (lit review 52)

Placeholder

### iPAM

Placeholder

### 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 1.5.7.1:

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| Figure 1.5.7.1: 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 hCAAR system uses a novel form of Impedance Control as the low-level control strategy whereby the motor current draw at each joint 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 block diagram for this arrangement is shown by figure 1.5.7.2:

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| Figure 1.5.7.2: 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 game. The second mode is passive where no assistance is provided, which is used to collect data about patient progress.

MEDICAL TRIALS

### RUPERT (Lit Review 77)

Placeholder

# References

* Coleman, E.R., Moudgal, R., Lang, K., Hyacinth, H.I., Awosika, O.O., Kissela, B.M. and Feng, W., 2017. Early Rehabilitation After Stroke: a Narrative Review. *Current atherosclerosis reports*, *19*(12), p.59.
* Culmer, P.R., 2007. *Development of a Cooperative Robot System to Aid Stroke Rehabilitation* (Doctoral dissertation, University of Leeds).
* Culmer, P.R., Jackson, A.E., Makower, S., Richardson, R., Cozens, J.A., Levesley, M.C. and Bhakta, B.B., 2010. A control strategy for upper limb robotic rehabilitation with a dual robot system. *IEEE/ASME Transactions on Mechatronics*, *15*(4), pp.575-585.
* Duffau, H., 2006. Brain plasticity: from pathophysiological mechanisms to therapeutic applications. *Journal of clinical neuroscience*, *13*(9), pp.885-897.
* Firouzy, S., 2011. *Control Algorithms to Improve the Dynamic Performance of Robotic Rehabilitation Devices* (Masters dissertation, University of Leeds (School of Mechanical Engineering)).
* Hogan, N. and Buerger, S.P., 2004. Impedance and interaction control. In *Robotics and automation handbook* (pp. 375-398). CRC Press.
* Hogan, N., 1984, June. Impedance control: An approach to manipulation. In *American Control Conference, 1984* (pp. 304-313). IEEE.
* Hogan, N., 1984. Impedance control of industrial robots. *Robotics and Computer-Integrated Manufacturing*, *1*(1), pp.97-113.
* Hogan, N., Krebs, H.I., Charnnarong, J., Srikrishna, P. and Sharon, A., 1992, September. MIT-MANUS: a workstation for manual therapy and training. I. In *Robot and Human Communication, 1992. Proceedings., IEEE International Workshop on* (pp. 161-165). IEEE.
* Hogan, N., Krebs, H.I., Sharon, A. and Charnnarong, J., Massachusetts Institute of Technology, 1995. *Interactive robotic therapist*. U.S. Patent 5,466,213.
* Hogan, N., Krebs, H.I., Sharon, A. and Charnnarong, J., Massachusetts Institute of Technology, 1995. *Interactive robotic therapist*. U.S. Patent 5,466,213.
* Krebs, H.I., Ferraro, M., Buerger, S.P., Newbery, M.J., Makiyama, A., Sandmann, M., Lynch, D., Volpe, B.T. and Hogan, N., 2004. Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus. *Journal of NeuroEngineering and Rehabilitation*, *1*(1), p.5.
* Kreisel, S.H., Hennerici, M.G. and Bäzner, H., 2007. Pathophysiology of stroke rehabilitation: the natural course of clinical recovery, use-dependent plasticity and rehabilitative outcome. *Cerebrovascular diseases*, *23*(4), pp.243-255.
* Lawrence, E.S., Coshall, C., Dundas, R., Stewart, J., Rudd, A.G., Howard, R. and Wolfe, C.D., 2001. Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke*, *32*(6), pp.1279-1284.
* Lee, S., Bae, S., Jeon, D. and Kim, K.Y., 2015. The effects of cognitive exercise therapy on chronic stroke patients’ upper limb functions, activities of daily living and quality of life. *Journal of physical therapy science*, *27*(9), pp.2787-2791.
* Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy, A. and Leonhardt, S., 2014. A survey on robotic devices for upper limb rehabilitation. *Journal of neuroengineering and rehabilitation*, *11*(1), p.3.
* Marek, S.M., Cramer, J.T., Fincher, A.L., Massey, L.L., Dangelmaier, S.M., Purkayastha, S., Fitz, K.A. and Culbertson, J.Y., 2005. Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. *Journal of Athletic Training*, *40*(2), p.94.
* Micera, S., Carrozza, M.C., Guglielmelli, E., Cappiello, G., Zaccone, F., Freschi, C., Colombo, R., Mazzone, A., Delconte, C., Pisano, F. and Minuco, G., 2005. A simple robotic system for neurorehabilitation. *Autonomous Robots*, *19*(3), p.271.
* Morreale, M., Marchione, P., Pili, A., Lauta, A., Castiglia, S.F., Spallone, A., Pierelli, F. and Giacomini, P., 2016. Early versus delayed rehabilitation treatment in hemiplegic patients with ischemic stroke: proprioceptive or cognitive approach. *Eur J Phys Rehabil Med*, *52*(1), pp.81-9.
* Moskowitz, M.A., Lo, E.H. and Iadecola, C., 2010. The science of stroke: mechanisms in search of treatments. *Neuron*, *67*(2), pp.181-198.
* Office for National Statistics. 2018. *Overview of the UK population: November 2018*. [Online]. [Accessed 13 November 2018]. Available from: <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/november2018>
* Ott, C., Mukherjee, R. and Nakamura, Y., 2010, May. Unified impedance and admittance control. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on Robotics and Automation* (pp. 554-561). IEEE.
* Richardson, R., 2001. *Actuation and control for robotic physiotherapy* (Doctoral dissertation, University of Leeds).
* Sivan, M., Gallagher, J., Makower, S., Keeling, D., Bhakta, B., O’Connor, R.J. and Levesley, M., 2014. Home-based Computer Assisted Arm Rehabilitation (hCAAR) robotic device for upper limb exercise after stroke: results of a feasibility study in home setting. *Journal of neuroengineering and rehabilitation*, *11*(1), p.163.
* Sommerfeld, D.K., Eek, E.U.B., Svensson, A.K., Holmqvist, L.W. and von Arbin, M.H. 2004. Spasticity after stroke: its occurrence and association with motor impairments and activity limitations. *Stroke*, 35(1), pp.134-139.
* Stroke Association. 2017. *Current, future and avoidable costs of stroke in the UK*. [Online]. London: Stroke Association. [Accessed 20 November 2018]. Available from: <https://www.stroke.org.uk/sites/default/files/costs_of_stroke_in_the_uk_report_-executive_summary_part_2.pdf>
* Stroke Association. 2018. *State of the Nation. Stroke Statistics February 2018*. [Online]. London: Stroke Association. [Accessed 13 November 2018]. Available from: <https://www.stroke.org.uk/system/files/sotn_2018.pdf>
* Van Peppen, R.P., Kwakkel, G., Wood-Dauphinee, S., Hendriks, H.J., Van der Wees, P.J. and Dekker, J., 2004. The impact of physical therapy on functional outcomes after stroke: what's the evidence?. *Clinical rehabilitation*, *18*(8), pp.833-862.
* Xu, X.M., Vestesson, E., Paley, L., Desikan, A., Wonderling, D., Hoffman, A., Wolfe, C.D., Rudd, A.G. and Bray, B.D., 2018. The economic burden of stroke care in England, Wales and Northern Ireland: Using a national stroke register to estimate and report patient-level health economic outcomes in stroke. *European stroke journal*, *3*(1), pp.82-91.