

Development of the iPAM MkII System and Description of a Randomized Control Trial with Acute Stroke Patients

A.E. Jackson, M.C. Levesley
School of Mechanical Engineering
University of Leeds
Leeds, UK

J.A. Cozens
Department of Rehabilitation Medicine
Grampian NHS
Aberdeen, UK

S.G. Makower
Leeds Community Healthcare NHS Trust
Leeds, UK

B.B. Bhakta
Faculty of Medicine and Health
University of Leeds and
Leeds Teaching Hospitals Trust, UK

Abstract—iPAM (intelligent Pneumatic Arm Movement) is a dual robot system for providing assistive upper-limb exercise to people with arm weakness as a result of stroke. This paper highlights refinements made to the system in the development of iPAM MkII. The rationale of an on-going random control trial using the iPAM MkII is also presented.

Keywords—rehabilitation; robotics; stroke; randomized control trial; upper-limb

I. INTRODUCTION

In the UK, stroke is the most common cause of adult disability; some 111,000 people have a stroke each year [1]. Of those who survive, up to 85% are left with some degree of paresis of the upper limb [2] with a quarter of them reporting some level of upper limb disability five years post-stroke [3]. This costs the UK health and social care system over £2.5bn each year in direct costs and £1.97bn costs through lost productivity and dependency [1]. Rehabilitation following stroke aims to maximise patients' independence. Re-learning of motor skills involving the paretic arm is a common feature of rehabilitation programmes, using either the same approach as before the stroke, or an adapted approach as the neurological deficit dictates. Studies in stroke patients show that increasing the level of physical therapy can improve some aspects of motor recovery [4,5]. Rate of progress towards greater skill depends upon the quantity of practice [6]; this general principle is confirmed for stroke patients by studies which have shown that increasing physical therapy can improve some aspects of motor recovery. Unfortunately limited resources leads to a reduction in the intensity and frequency of therapeutic intervention delivered to patients.

An approach to address the shortcomings of over stretched rehabilitation services is to augment conventional physiotherapy with therapy delivered by robotic systems. A

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review of upper-limb robotic stroke rehabilitation [7] cited 28 robotic systems currently either commercially available or under development. The majority of these upper-limb robotic systems fall into one of two categories, exoskeleton systems or end-effector based systems. The MIT-Manus [8] and ARM-Guide are two systems that fall in to latter category. Both are planar-manipulators that attach to the distal segment of the upper limb to provide assistive movement. The MIT-Manus has been marketed as the InMotion ARMTM and has had extensive clinical use. ARM-Guide is a linear slide mechanism that allows straight line movement in a plane that can be rotated manually.

These systems and several others are included in a systematic review of the effect of robot-assisted upper-limb recovery after stroke, undertaken by Kwakkel et al. [10]. The outcomes of several Randomized Control Trials (RCTs) are presented. The systems included were the MIT-Manus, MIME, ARM-Guide, Bi-Man-Track and the InMotion² Shoulder-Elbow Robot, with a total of 218 participants. Conclusions of the covered RCTs include: repetitive movements seem to be primary stimuli to recovery (ARM Guide); intensive therapy leads to better recovery after stroke (MIT-Manus); robot-assisted treatment gains exceeded those expected from spontaneous recovery (MIME). No substantial improvements in ADLs were produced which would not necessarily be expected as the systems focus on gross upper limb movement, not hand function, essential for many ADLs.

Another RCT [11] utilizing the suite of InMotion systems was undertaken involving 127 chronic stroke patients, 49 of whom were randomized to robot-assisted therapy, 50 to intensive comparison therapy and 28 to usual care. Robot assisted therapy and intensive comparison therapy both delivered up to 36 hour-long sessions of intervention over a 12

week period. Both consisted of a matched schedule and intensity of movement. The study demonstrated no significant difference between intensive robot therapy and intensive comparison therapy, while an improvement was demonstrated at 36 weeks over patients receiving normal care.

All of the above systems provide assistance in the coordinate frame of the robot end-effector utilising a single point of attachment (although some of the systems employ a sling mechanism to provide passive support at the shoulder). With a single point of attachment, the limb is under constrained and under supported. This is where exoskeleton systems have an advantage, utilising two or more contact points on the patient's arm. Pneu-WREX [12] and ARMin [13] are both exoskeleton systems, the former a five DoF exoskeleton actuated by pneumatic cylinders while the latter incorporates seven active DoF using wire-driven rotary joints (although two are DoF dependent). The exoskeleton system has the advantage that the robot joints coincide with the human joints, so direct control and coordination of each joint is possible. However, as they are required to adapt to a wide range of patient limb sizes while aligning with the shoulder joint, they tend to be mechanically complex systems.

The intelligent Pneumatic Arm Movement (iPAM) system [14], developed at the University of Leeds, utilises two custom-made robotic arms to provide a system for delivering physiotherapist prescribed rehabilitation exercise. By using dual attachment points, it can provide coordinated joint control based around the human limb while being suitable for a large range of patients. No mechanical adjustments to the system are required between patients regardless of limb size, these are taken into account in software, reducing changeover time. The system allows exercise to be delivered in 3D space rather than in one plane providing a wider range of therapeutic movements which can be tailored to patient upper-limb deficits. This paper highlights the design changes undertaken between the MkI and MkII systems and introduces the details of a RCT currently underway, utilizing three iPAM MkII systems integrated into acute stroke services within the UK National Health Service (NHS).

II. iPAM Mk I SYSTEM

iPAM (figure 1) consists of two identical pneumatically powered, three rotary-joint robotic arms that are attached the upper limb via two specially designed orthoses. One attaches close to the patient's wrist while the second at the midpoint of the upper-arm, mimicking the manner in which a physiotherapist (PT) grasps a patient's arm to facilitate exercise. The configuration allows the control of the orthoses of each robot in Cartesian space while the design of the orthoses allows three passive rotational DoF aligned through the centre of the patient's limb. Rotary sensors measure the rotation of the six active robot joints while two six-DoF force/torque transducers record the relative forces between the robot and the patient's limb. As the only link between the two orthoses is the patient's arm, it is essential that the robots coordinate effectively to prevent undesirable forces being applied to the limb. To accomplish this, a novel control scheme was

implemented that operates around the DoF of the human joints rather than the Cartesian endpoints of the robots. With the robots capable of controlling three DoF each, it is possible to constrain six DoF of the human arm. This requires an accurate model of the upper-limb. Details of the low-level control strategy and the upper-limb model can be found in [15].

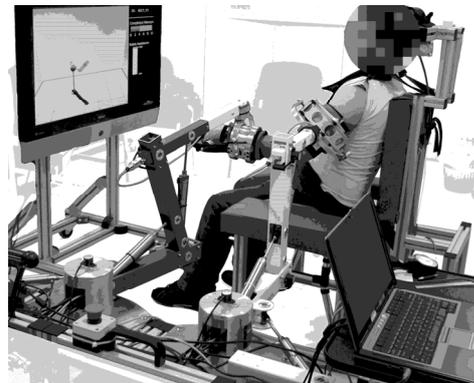


Fig. 1. iPAM MkI Robotic Rehabilitation system

When not undertaking active exercise, the system operates in a passive warm-standby state where the actuators provide sufficient force to counteract the weight of the robot arms and orthoses. The inherent back-driveability of the pneumatic system allows the system to be freely moved by the patient and PT. Exercises were manually recorded by the PT guiding the patient's limb through the workspace while recording target positions with a footswitch switch. Once recorded, the trajectory can be replayed by the system providing a PT defined level of assistance (using admittance control) to reach the targets. A clinician interface allows the PT to prescribe sets of these pre-recorded exercise tasks and view performance outcomes. A Patient Interface displays a model of the patient's limb in a virtual "3D" workspace and the targets that the patient must reach to. It also provides feedback as to their performance on each task attempt [16].

The system was developed with extensive end-user involvement. The Rehabilitation Technologies User Group (RTUG) was established at the University of Leeds. It consists of clinicians, physiotherapists, engineers, psychologists and stroke patients and their carers. The group met regularly to inform aspects of the design. Further details of the design process of the iPAM system can be found in [14].

iPAM MkI has been used by 26 patients with stroke through 2 pilot studies (10 patients in one study and 16 in a second). Over these two studies iPAM safely delivered over 300hrs of assistive exercise to patients with a range of arm sizes and movement deficits.

III. DEVELOPMENT OF iPAM MkII.

In order to improve the reliability and ease-of-use of the iPAM system; making it suitable for operation within acute stroke services without the supervision of an engineer, a number of refinements had to be made. The feedback gathered from participants in the second pilot study, whilst largely positive [17], highlighted some features of the system that required attention. This, along with RTUG involvement and

research PT experience has helped inform the development of the iPAM MkII system. The main refinements are introduced below along with the rationale for the changes.

A. Robot configuration and design

The configuration of the robot arms has remained the same with the exception of the base joint which no rotates between -20° and $+30^\circ$. This reduction from $\pm 30^\circ$ was based on data recorded during the iPAM MkI clinical studies [18]. The positions of the base joint actuators were altered, housing them within the base unit of the robot trolley, reducing the width of the overall system and helping to protect them from damage. The robot arms have been refined to provide a cleaner look, including adding bearing covers and endcaps and routing all-wiring through the robot arms themselves, reducing the chance of a user accidentally disconnecting a sensor.

The base-unit features an adjustable monitor mount that holds the clinician interface screen that allows the clinician to comfortably interact with the system either sitting or standing and also to swivel it round so it is suitable for left and right sided operation. Three lockable access doors allow the engineer access to the system but prevent unauthorized access. The whole system is on lockable castors allowing the system to be readily moved around the ward when required. The redesigned system can be seen in Figure 2.



Fig. 2. The iPAM MkII Robotic Rehabilitation System

B. Refinement to upper and lower orthoses.

Experience of using both orthoses in the previous study highlighted issues regarding their size and the ease of attachment. When patients with shorter limb lengths used the system close to the body, the width of the upper orthosis outer cradle often caused it to come into contact with the distal segment of the lower robot. The U-shaped outer cradle of the orthosis has been replaced with a cantilever arm that takes approximately 20mm from the distal end of the upper orthosis reducing the likelihood of the upper orthosis “clashing” with the lower arm attachment. Like the upper orthosis, the lower orthosis has also been cantilevered from the robot side. This improves the ability of the patient to have an unobstructed view of the hand while undertaking the reaching exercises. It also allows the forearm orthosis to come closer to the body increasing the size of the patient exercise workspace. In both orthoses, a modified blood pressure cuff is incorporated that is inflated, allowing variation in upper-limb girth while providing a comfortable interface between robot and patient.

The strapping of the two orthoses was altered to make both easier to attach. Spring pins were incorporated to allow easy removal and reattachment of the orthoses from the robot arms without the need for tools. This further reduces the time required to switch the robot from left to right sided operation. Internal connectors ensure electrical connections are automatically made when orthoses are in place.

A keyway was introduced to the inner cuff of the lower orthosis that allows a handle insert to be securely attached into it. The insert also houses a 3-axis accelerometer to monitor forearm pronation/supination. This handle can be attached and detached once the patient is in the system making it easier to attach patients with high tone at the wrist. It can be completely removed to allow free hand grasping.



Fig. 3. The redesigned upper and lower orthoses.

C. Refinement of calibration process

For iPAM to operate correctly, the patient’s arm must be registered within the system to calibrate the human arm model used by the controller with the real arm. The first stage of this is to measure the relative position of the orthoses to bony markers on the patient’s arm. In the previous system, this was accomplished using a metal rule butted against the relevant orthosis and the distance to the bony marker on the elbow (medial epicondyle) read by sight. The measurements were then manually inputted to the computer. This process is prone to error, leading to potentially inaccurate calibration.

The second stage in the calibration process determines the position of the shoulder relative to the robot; the shoulder-robot offset. To obtain this on iPAM MkI, the patient was required to lean over in order to get the upper arm as close to vertical as possible (as judged by the PT). As the relative distance from the upper orthosis to the shoulder had been measured and the position of the upper orthosis in robot coordinates known, the shoulder-robot offset could be calculated. A shoulder monitor consisting of three pull-cord potentiometers attached to a cradle is taped to the patient shoulder. This measures relative displacement of the shoulder in 3 DoF. At this point in the calibration process the measurement given by the shoulder monitor was zeroed. The patient was then asked to return to the upright position and the relative change in shoulder position was added to the currently recorded shoulder-robot offset to give the calibrated shoulder-robot offset. The shoulder monitor was then zeroed a second time.

Inaccuracies in step one measurements and difficulty determining the vertical orientation of the arm led to inaccuracies in the calibrated arm model. This often led to the process being undertaken a number of times before satisfactory

calibration was achieved. In addition the requirement for the patient to lean over introduced an unnecessary risk. As a result a new calibration method was developed that does not require the patient to move within the system aside from positioning their arm in a comfortable position by their side. Two new calibration tools were designed to aid this process.

Calibration tool 1: A measurement box that houses a pull-cord potentiometer and a push button. This is placed in position on each orthosis in turn and used to measure the relative position of the lower and upper orthoses to the elbow and shoulder respectively (Figure 4). The system only allows a measurement to be taken when the device is in the correct position on the orthoses, this replaces the use of a ruler and entering the value into the computer manually.

Calibration tool 2: A second tool was developed that contains a 3-axis accelerometer and push button. The PT lines the tool parallel with the upper arm. The accelerometers measure the shoulder abduction and flexion, which are then used to calculate the shoulder-robot offset with greater accuracy. During this process, the Patient Interface displays images of the current upper-limb model with shoulder flexion and abduction values. By comparing these images with the actual arm, the PT can improve the success of calibration (Figure 4). The system allows a measurement to be taken when Calibration tool 2 is in the correct position on the upper orthosis. This replaces the need for the patient to lean over during calibration as the upper-arm no longer needs to be vertical. It does, however require slightly more training to familiarize the PT with the method of comparing the actual arm and its on-screen representation.

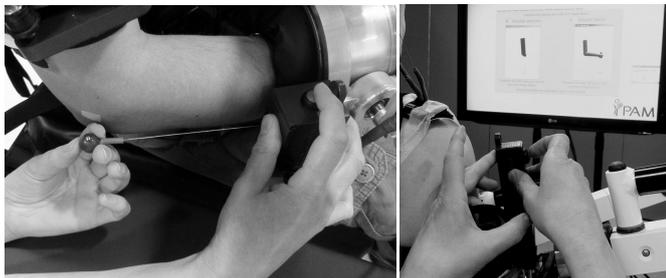


Fig. 4. Calibration tool 1 measuring relative position from lower orthosis to medial epicondyle and calibration tool 2 measuring upper arm angles and comparing patient arm to the human arm model on the Patient Interface.

D. The pneumatic system

Issues regarding the reliability and response of the pressure regulating control valves used on iPAM MkI meant new valves were needed to allow the systems to run for extended periods away from the University laboratory. A review of available pressure regulating control valves was undertaken. A static test rig was used to assess the frequency response of the valves by measuring the resultant output force of a constrained cylinder at different fill volumes. The resulting valve chosen was the MAC PPC036 which fulfilled the requirements for speed and reliability.

Analysis of end-effector forces measured during the recording of therapist prescribed exercises [18] demonstrated that the existing anti-stiction Airpot Airpel M24 cylinders used

on iPAM MkI provided the sufficient force and performance for the system. A stand-alone compressor was included that delivers dry, medical quality compressed air completing the pneumatic system.

E. Seating system

Feedback on iPAM MkI seating system was generally negative in terms of both comfort and aesthetics. It consisted of an off-the-shelf shower chair located in an aluminium frame which incorporated arm and back rests and the shoulder monitor giving the impression of an “electric chair”. For MkII, it was decided that the use of a wheelchair offered a good solution, as it allows a quick changeover between left and right sided operation and give the option for the patient to transfer to the chair away from the system before being wheeled into place. The main component of the wheelchair that required redesign was the chair’s back rest. Due the position and movement of the upper arm and orthosis during exercise, it is not possible to have a standard-width back rest; hence a new back rest was designed. The redesign provides sufficient support to the patient while allowing a therapeutic range of upper-limb movement. Mounts for the shoulder position monitor were incorporated on both sides of the back rest while the existing arm rests were adapted such that the patient stop button could be easily mounted on the patient’s unaffected side. A new wheelchair harness was also included for those patients with lesser degree of sitting balance and to restrict compensatory trunk movement during the exercises.

A docking station incorporating a robot-side arm rest and storage for the new calibration tools was developed. Its main purpose is to correctly position the wheelchair relative to the robots. While the calibration process allows for small variations in the wheelchair’s position, by locating the wheel chair correctly, the patient’s shoulder is located approximately in the centre of the robot workspace allowing both lateral and medial movements. The docking station has a channel for the location of the robot-side wheels of the wheelchair.

F. Software and control hardware

The standalone laptop used in iPAM MkI, while sufficient for the software, posed a security risk as it could easily be removed from the system. For iPAM MkII a small form factor PC was integrated into the robot base unit. The real-time PC used to run the low-level LabVIEW control software on iPAM MkI has been replaced by a National Instruments PXI system. This provides reliable operation of the low-level control software, essential for safety. The PXI contains an FPGA (Field Programmable Gate Array) card that allows the programming of a configurable integrated circuit with software. Once implemented, the code on the FPGA runs as if it is a piece of hardware. As a result it can run safety critical code that is independent from the control software. The use of the FGPA allows the system to react within 1 μ s to the emergency stop being pressed or a drop in supply pressure.

The Patient Interface (Figure 5) was improved to provide four different environments in which the patient can exercise: beach, gym, city or countryside. A dial presenting the patient’s forearm pronation / supination, measured by the patient handle 3-axis accelerometers, is included to encourage them to maintain a neutral hand position.

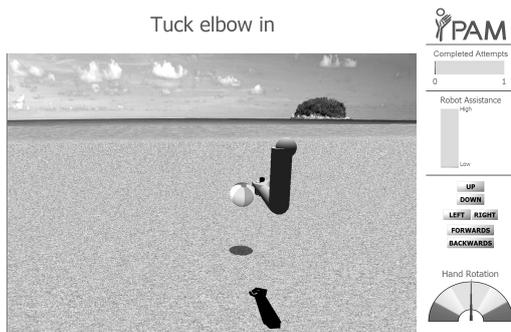


Fig. 5. Patient Interface screen used to display a representation of the patient arm virtual targets during active exercises.

G. Safety systems

A dedicated safety module with priority error handling was introduced to the low-level software module. This allows the system to handle a number of errors or warnings, giving priority to the most serious error. 22 custom error codes were used to allow the system to use inbuilt error handling to ensure the system always behaves in a safe manner and can be shut down safely every time, depending on the nature of the error. A warning would result in the suspension of active exercises returning the robot to a passive state (e.g. excessive shoulder movement or user pressing the patient stop button) while an error is a safety critical event that safely shuts down the system to prevent patient harm (e.g. excessive force measured in a passive state or critical drop in supply pressure). A sensor check routine was implemented to check the operation of the robot joint sensors, force sensors and the pneumatic valves each time the system powers up to ensure correct operation prior to patient attachment. An audible alarm sounds in case of any error or warning to alert the PT of the event. A log file is written to after each event so that a record can be kept of each error or warning as it occurs.

H. High-level control

The exercises which iPAM MkI provided needed to be recorded by the therapist by manually moving the patient's arm through the desired trajectory while attached to the robot. The system would record these trajectories that could then be played back to the patient with a PT specified level of assistance. This allowed the therapist to build up a bank of patient-specific exercises. This increased the time required for the patient to start undertaking exercises as all exercises needed to be explicitly defined by the PT.

The iPAM MkII system features a new clinician interface (SILCK Clinic) which allows the treating therapist to interact more efficiently with the system. iPAM delivers assistance according to the therapist's prescription (SILCK Clinic) and the clinical state of the patient (degree of weakness, spasticity level). These exercise programs automatically adapt to patient progress, either by increasing the workspace of the exercises or by lowering the assistance provided by the robot. Patient progress is judged in terms of target attainment. It also varies the representation of the computer targets on the patient interface to maintain interest, adjusting the targets during sequential exercises autonomously within predefined therapy prescriptions. This reduces the burden on therapy staff as the

patient can receive a varied and adaptive exercise program without the need for therapist intervention. The clinician interface still allows explicitly defined exercise tasks while also providing the automated exercises tasks based on particular treatment strategies. iPAM is intended to be operated under indirect therapy supervision. For example, the patient may exercise using the iPAM in the rehabilitation therapy area while the therapist is treating another patient nearby.

IV. RANDOMIZED CONTROL TRIAL RATIONALE

The iPAM system is currently being utilised in a randomized control trial. Three iPAM MkII systems have been produced and installed in acute stroke services within three different NHS trusts. Below are the details of how the trial will run.

A. RCT aims

The primary aims of the RCT are:

- To obtain information about the feasibility of undertaking a controlled clinical trial of iPAM within NHS stroke rehabilitation service to aid development of a future Phase 3 trial design.
- To obtain clinical outcome data to inform sample size calculations in the context of a future Phase 3 clinical trial.
- To obtain information about the practicalities of delivering the intensity and duration of iPAM intervention within NHS stroke rehabilitation service.
- To assess the safety of device use within an NHS stroke rehabilitation environment.

The secondary aims are to investigate the implementation of iPAM in NHS early stroke rehabilitation services:

- To obtain end user opinion (NHS therapy staff) about the training package and setup phase of iPAM within a NHS stroke rehabilitation service.
- To obtain end user opinion (person with stroke, NHS therapy staff) about the use of iPAM to treat people in the early stages of stroke recovery within a NHS stroke rehabilitation service.

B. Trial design

A prospective, randomised, controlled trial of NHS rehabilitation treatment alone versus NHS rehabilitation treatment with up to 6 weeks iPAM treatment (up to 30 sessions) for those admitted to acute stroke services after new stroke. 90 people with stroke admitted to acute stroke services will be recruited. Each participant will be randomised within 1–6 weeks post stroke (in certain situations e.g. due to weekends or bank holidays, it is acceptable to allow 7 – 42 days between stroke and randomisation). The trial is being undertaken in three acute stroke units or acute rehabilitation services within the NHS.

C. Intervention

1) *Active group*: each patient recruited to the iPAM group will receive one to two exercise sessions of iPAM delivered therapy per day for up to 30 days on top of usual therapy. Each exercise session will be approximately 45–60 minutes or as low as 10 minutes depending on the patient's clinical state. Each patient is likely to receive approximately 30 robot

treatments during their participation. iPAM intervention with usual NHS rehabilitation treatments will be continued for a maximum of six weeks as long as it is deemed that the patient would benefit from ongoing rehabilitation. The duration of treatment will be less if the patient: completes 30 iPAM exercise sessions; no longer requires physiotherapy; is discharged from hospital (patients will be offered the opportunity to come back to hospital to complete their course of trial therapy); or there is lack of stroke unit staff time to deliver the intervention. The decision about need for rehabilitation interventions will be made by the treating clinicians, therapists and nurses in consultation with patients and families as part of the routine management of the patient.

2) *Control group*: The control group receive usual therapy plus additional therapy time (equivalent to the time it takes for a therapist to set a patient up in the iPAM system – approximately 15 minutes). It is estimated from previous patient experience that it takes a maximum of 15 minutes to set up the iPAM system and prescribe iPAM exercises for each treatment session (some sessions take a lot less time particularly as the patient and therapists become comfortable at using the system). Therefore on a weekly basis, a maximum of 2.5 hours (maximum of two 15 minutes sessions, 5 times per week) extra therapy treatment per week will be allocated to the control group. This extra time therapy may be combined to make extra or longer usual therapy sessions. This provides a matched burden on physiotherapy resource between the active and control group.

D. Outcomes

The primary outcome measure to be used will be the Fugl Meyer (Upper limb section), a clinically meaningful response (defined as ≥ 3 point improvement in Fugl Meyer upper limb score [11]) will be looked for from baseline to 10 weeks post randomization as well as individual segment scores. A number of secondary outcome measures will be employed: Barthel Index; Stroke Impact Scale; ABILHAND; EQ-5D. Safety issues that arise will be reported by the treating therapist. Implementation success will be assessed through standardised Likert response questionnaires. Questions include ease of use, nature of exercise and fit with routine clinical service. The iPAM system will also record numerous quantitative parameters over the course of the trial, such as duration of exercise, assistive forces provided and range of movement.

V. CONCLUSION

This paper has presented the refinements to the iPAM dual robot system that were required to allow for deployment into an acute stroke service within the UK NHS. These were needed to improve usability, reliability and offer further safety features. The rationale of the Randomized Control Trial was introduced. One outcome of the trial is to demonstrate that the use of a robotic system can improve the patient outcome for the same level of physiotherapy resource. The trial is currently recruiting across three NHS trusts.

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REFERENCES

- [1] P. Scarborough, V. Peto, P. Bhatnagar, A. Kaur, J. Leal, R. Luengo-Fernandez, A. Gray, M. Rayner, S. Allender, "Stroke Statistics", Department of Public Health, University of Oxford, 2009
- [2] C. E. Skilbeck, D. T. Wade, R. Langton-Hewer, V. A. Wood, "Recovery after stroke". *Journal of Neurology, Neurosurgery and Psychiatry*. Vol 46 pp. 5-8. 1983.
- [3] J. M. Geddes, J. Fear, A. Tennant, A. Pickering, M. Hillman, M. A. Chamberlain, "Prevalence of self reported stroke in the population of Northern England". *Journal of Epidemiol Community Health Med*. Vol. 50, pp. 140-143, 1996.
- [4] G. Kwakkel, R. C. Wagenaar, J. W. R. Twisk et al. "Intensity of leg and arm training after primary middle cerebral artery stroke: a randomised trial." *Lancet* 1999;354:189-194.
- [5] A. Sunderland, D. J. Tinson, E. L. Bradley et al. "Enhanced physical therapy improves recovery of arm function after stroke. A randomised controlled trial." *J Neurol Neurosurg Psychiatry* 1992;55(7):530-535.
- [6] A. Sterr, T. Elbert, I. Berthold et al. "Longer versus shorter daily constraint induced movement therapy of chronic hemiparesis: An exploratory study." *Arch Phys Med Rehabil*. 2002;83:1374-1377.
- [7] R. C. V. Loureiro, W. S. Harwin, K. Nagai, M. Johnson, "Advances in upper-limb stroke rehabilitation: a technology push". *Medical & Biological Engineering & Computing*, Oct 2011, 49(10), pp 1103-1118.
- [8] H. I. Krebs, M. Ferraro, S. P. Buerger, M. J. Newbery, A. Makiyama, M. Sandmann, D. Lynch, B. T. Volpe, N. Hogan, "Robotic upper-limb neurorehabilitation in chronic stroke patients". *Journal of NeuroEngineering and Rehabilitation*, 1:5 2004.
- [9] D. J. Reinkensmeyer, C. D. Takahashi, W. K. Timozzyk, A. N. Reinkensmeyer, L. E. Khan, "Design of robot assistance for arm movement therapy following stroke." *Advanced Robotics*, Vol. 47(7), pp. 625-637, 2001.
- [10] G. Kwakkel, J. K. Kollen, H. I. Krebs, "Effects of robot assisted therapy on upper limb recovery after stroke: A systematic review", *Neurorehabilitation and Neural Repair*, Vol. 22, pp. 111-121, 2007.
- [11] A.C. Lo et al. "Robot-Assisted Therapy for Long-Term Upper-Limb Impairment after Stroke." *N Engl J Med* 2010;362:1772-83.
- [12] R. J. Sanchez Jr., E. Wolbrecht, R. Smith, J. Liu, S. Rao, S. Cramer, T. Rahmen, J. E. Bobrow, D. J. Reinkensmeyer, "A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design." *Proceedings of 9th International Conference on Rehabilitation Robotics*, 2005. pp. 500-504.
- [13] T. Nef, M. Guidali, V. Klamroth-Marganska, R. Riener, "ARMin – Exoskeleton Robot for Stroke Rehabilitation." *Proceedings of World Congress on Medical Physics and Biomedical Engineering*, 2009. pp. 127-130.
- [14] A. E. Jackson, R. J. Holt, P. R. Culmer, S. G. Makower et al. "Dual Robot System for Upper Limb Rehabilitation after Stroke: The Design Process." *Proceedings of the IMechE. Part C - Journal of Mechanical Engineering Science*. Volume 221, No. 7, 2007, pp. 845-857.
- [15] P. R. Culmer, A. E. Jackson, J. Savage, M. C. Levesley, R. Richardson, J. A. Cozens, B. B. Bhakta, "An Admittance Control Scheme for a Robotic Upper-Limb Stroke Rehabilitation System." *Proceedings of the 27th Annual Conference IEEE Engineering in Medicine and Biology* 2005. pp. 5081-5084.
- [16] S. Kemna, P. R. Culmer, A. E. Jackson, S. G. Makower et al "Developing a User interface for the iPAM Stroke Rehabilitation System." *Proceedings of the 11th International Conference on Rehabilitation Robotics* 2009. pp. 879-884.
- [17] A. E. Jackson, S. G. Makower, P. R. Culmer, et al, "Acceptability of robot assisted active arm exercise as part of rehabilitation after stroke." *Proceedings of the 11th International Conference on Rehabilitation Robotics* 2009. pp. 103-108.
- [18] A. E. Jackson, P. R. Culmer, M. C. Levesley, S. G. Makower, J. A. Cozens, B. B. Bhakta, "effector force requirements to enable robotic systems to provide assisted exercise in people with upper limb impairment after stroke" *Proc. of 12th Int Conf on Rehabilitation Robotics* 2011.