Initial patient testing of iPAM - a robotic system for Stroke rehabilitation

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Abstract— **iPAM is a dual robotic system currently being developed in the UK under a NHS New and Emerging Applications of Technologies (NEAT) grant. The aim of the system is to provide assistive upper-limb therapeutic excercise for post-stroke rehabilitation. iPAM features two co-ordinated, pneumatically-actuated robotic arms which attach to the patient's forearm and upper-arm to provide assistance, mimicking the intervention of a physiotherapist. The system design and manufacture has been completed and the robot installed at a local hospital (St Mary's, Leeds PCT, UK) inside a community rehabilitation unit. The controller is currently developed and 'tuned' to provide gravity compensation for robots, removing any potentially damaging loads on the patient arm. The control scheme has been tested in simulation and using a mechanical arm model to ensure safe operation.**

Two small scale trials have been conducted to assess two facets of the robot design; firstly the mechanical design of the system to unimpede normal arm movement and secondly, its ability to provide varying levels of lift to the patient's arm to increase range of movement. The former of these trials compares free arm movement in healthy volunteers and Stroke patients with that when attached to iPAM. The robot was configured to compensate for its own weight, so the human upper-limb was unloaded. It was found that the robot had no significant affect on movement patterns. The second group of patient trials evaluated the operation of various levels of assistance against gravity. Patients were asked to point to a target with varying degrees of 'lift' applied to their upper and lower arm. In those patients with significant upper-limb impairment it was found that higher values of 'lift' improved the extent of reach but altered the movement pattern. Results from the trials demonstrated the suitability of certain modes of operation depending on the severity of patient disability.

I. INTRODUCTION

The challenges of how to provide frequent and effective therapeutic rehabilitation to those affected by stroke is a universal issue and one which will only amplify as the effects of an aging population are felt. At present around 300,000 people suffer the affects of stroke in the UK alone, with 85% of those experiencing a degree of arm paresis from the onset [1]. After 5 years, one in four still report difficulty using their paretic arm [2]. Rehabilitation programmes aim to increase patient's independence by focusing on everyday tasks of self care, domestic duties and recreation. Through the practice of these activities, the re-learning of motor skills can lead to a greatly increased capability. This places a significant burden on the National Health Service (NHS), with severely limited physiotherapy resources, patients do not spend enough time engaged in rehabilitation activities. Augmenting traditional phyical therapy with robot assisted therapy is one potential solution that is being investigated at several institutions worldwide.

One particular approach utilised is the single point of attachment system as seen on the MIT-Manus [3], Gentle/s [4] and UECM [5] robots. These systems rely on a single attachment point at the wrist, sometimes in conjunction with a passive sling mechanism at the upper arm to support the shoulder and offset some of the arm mass. A recent study [6] with the InMotion2 system (a commercial model of the MIT-Manus) demonstrated small but positive improvements in motor impairment scores for 27 moderate and chronic stroke patients. The Gentle/s robot system, which is based around a modified Haptic Master, has been utilised in a single case study, comparing improvement after a period of robot intervention compared to no intervention and sling suspension intervention. The investigation demonstrated the superiority of robot intervention in both cases [7]. The Upper Extremity Compound Movements (UECM) rehabilitation robot developed at Tsinghua University in China has a 2 DoF planar configuration. It can operate in both assistive and resistive modes depending on patient ability. A clinical trial has been undertaken with 23 chronic stroke patients. Results show the majority of patients experienced an improvement in motor function [8]. The results from all these trials demonstrate the efficacy of robot assisted physiotherapy.

In the above systems, the arm is controlled in terms of the end hand trajectory, as opposed to human limb co-ordination. A limitation of such systems is the inability to fully constrain the upper-limb. A single end effector position does not define specific elbow or shoulder rotations, hence joint co-ordination is not viable. In addition, assistive forces at the wrist in patients with elbow spasticity and low tone or subluxation at the shoulder, may lead to inappropriate levels of torque at the shoulder joint causing pain or discomfort. Conventional physiotherapy involves the PT acting at two contact points on the arm; one on the lower arm, close to the wrist and the second around the mid-point between elbow and shoulder. This allows the PT to fully constrain the orientation and position of the limb and co-ordinate the arm segments in a therapeutically meaningful manner.

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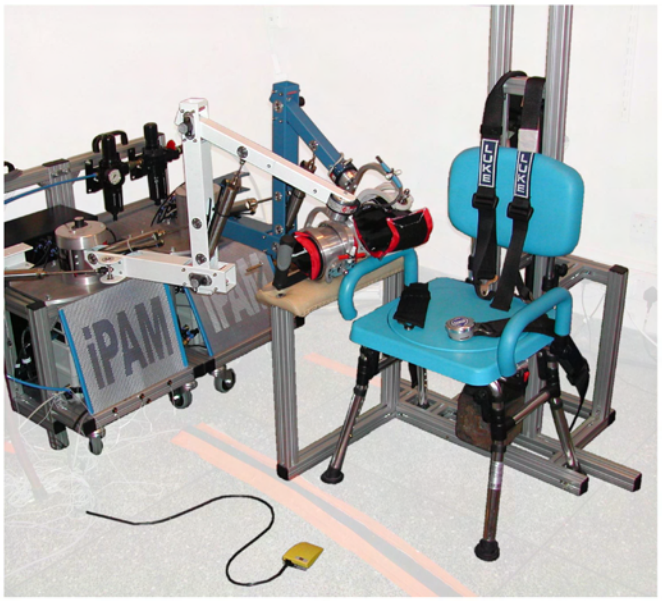


Fig. 1. The iPAM system

One solution to these problems has been addressed by the development of exo-skeleton type robot systems that are fitted along or around the limb to allow a greater degree of co-ordination. The Pneu-WREX [9], RUPERT [10] and ARMin [11] robot systems all adopt this approach. Pneu-WREX is a 5 DoF robot system made up from a pair of 4 bar linkages. It is actuated by pneumatic actuators while gravity compensation is provided by interchangeable springs. RUPERT (Robotic UPper Extremity Repetitive Therapy device) has 4 active DoF, although with only one degree at the shoulder, movements are restricted to planer movement with elbow extension, forearm pronation and wrist flexion. A second iteration is under development [12]. The ARMin system is a partial exo-skeleton system with 4 active DoF and 2 passive. Actuation is provided by cables driven by electric motors implemented through impedance control. Trials with the ARMin system demonstrated a decrease in the level of robot assistance during movements as the trial progressed, indicating some motor improvement [13]

II. iPAM DUAL ROBOT SYSTEM

The intelligent Pneumatic Arm Movement (iPAM) robotic system is a dual robot system (Fig. 1) for providing assistive therapeutic exercise for patients suffering from upper-limb paresis as a result of Stroke. Each of the robotic arms has 3 active DoF and assists the patient via a specially designed orthosis. The orthoses, attached via a pressure-cuff, are located near the wrist on the lower arm and midway between elbow and shoulder on the upper arm. The orientation of each orthosis is unconstrained, with each of the 3 rotational axes passing through the arm's centre. This allows the orthoses to align with the arm, regardless of end effector orientation. Actuation of each robot is provided by 3 pneumatic low-friction cylinders which are controlled using 6 proportional control valves. Position and force sensors are used to monitor

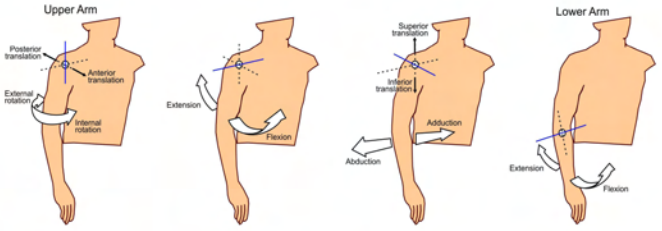


Fig. 2. The six DoF of the human arm controlled by iPAM

position of the human arm and forces applied to the patient arm by the robot system. The combination of the 3 powered DoF at the end of each robot arm allows control of 6 DoFs of the human arm attached. The degrees of freedom of the human arm are shown in Fig. 2. This configuration is analogous to the approach used by physiotherapists (PT) when holding the patient's limb segments during conventional upper-limb rehabilitation. Using the kinematic models of the robot and human arms with measurements from the angle sensors, it is possible to monitor the position of the end orthoses and the position of the patient arm. The resultant 6 DoF control gives the potential for a control strategy that facilitates coordinated movement of the arm as a whole, rather than just the movement of the distal segment (e.g. forearm or hand). This is a key aspect of the iPAM system. Additionally, active control of the upper arm robot also allows for full support of the shoulder complex during movement.

III. CONTROL SYSTEM

With two physically independent robots attached to the patient arm, effective co-ordination between each robot is paramount. Mis-alignment of the robot end-effectors could place undesirable torques onto the patient's limb. It is therefore necessary for the implemented control scheme to be co-operative. This requires a mapping from each robot's task space into a coordinate system representing the human arm. This has been achieved using a kinematic model of the human arm [14] as shown in Fig. 3. Utilising the kinematic model of the arm, and the system measurements, it is possible to determine both the positions and torques exerted on the limb. If trajectories are to be defined in human joint space, the next logical step is to provide assistance in the same co-ordinate system. An admittance control scheme has been developed that modulates the input trajectory for each DoF as a function of measured force/torque and takes the form:

$$\delta x = \frac{F}{Kx + sCx}$$

where K and C are stiffness and damping terms respectively. This allows the charactistics of assistance to be altered in each DoF of the human arm indepentently. For more details on the admittance control scheme see [15].

Initially for iPAM, three specific control schemes are to be implemented:

- Gravity compensation mode: Robot remains in gravity compensation mode, i.e. the robot actuates sufficiently,

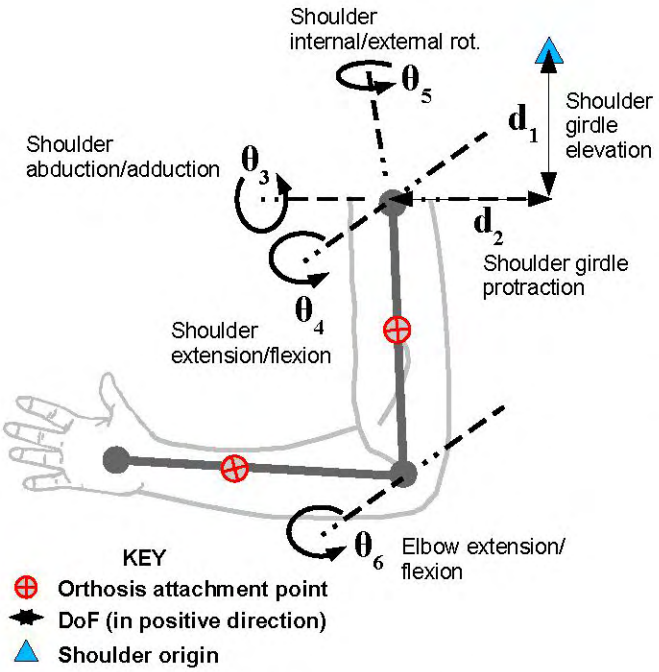


Fig. 3. 6 DoF kinematic arm model

depending on the orientation of the robot joints, to lift the weight of the robot itself and the orthoses. As such the robot feels weightless, but patient is free to move their arm to meet the desired targets. No assisted movement is provided by the robot

- Hand trajectory mode: Acts like a single point of attachment robot. Upper robot operates in gravity compensation mode while the lower robot operates a Cartesian admittance control scheme
- Joint control mode: Robot arms provide admittance control as outlined above about the human joints to provide coordinated movement

For the initial trials, only the first of these control schemes is utilised. An extension of this control scheme allows iPAM to offset some of the weight of the patient's arm too. This provides an effect similar to a sling suspension device.

IV. Preliminary Trials

Preliminary trials were conducted as part of a parallel process to collect qualitative data on user and therapist perception of the iPAM system and the procedures associated with it. The trials consisted of two distinct sets of experiments which formed the user involvement component of the user perception study.

A. Aims

The first experiment was a small scale investigation to determine whether a participants movements are comfortable and unimpeded by the robot system in its passive mode. This is of great importance because the design of the system depends upon not exerting forces or torques on the upper-limb unless explicitly desired by the control scheme. The second experiment is aimed to measure the effects on

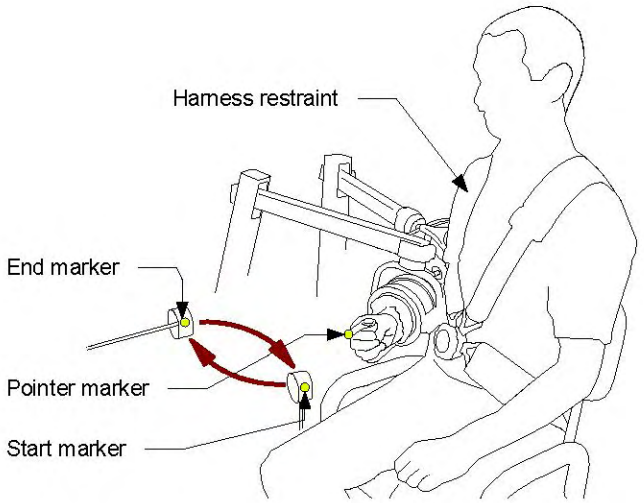


Fig. 4. The configuration of experiment 1

movements when varying degrees of robot assistance are applied to counteract the effects of gravity on the upper arm and forearm. In addition to the aims above, both experiments serve as a useful platform for data collection that can be used to further develop the various control modes of the robot.

B. Method

1) Experiment 1: A standardised movement task was constructed that could be performed both with and without the robot. The start and end-points of the movement were defined by two markers; the first was located in a comfortable position by the participant's waist, the second was offset distally, medially and superiorly from the first marker. A full movement cycle was performed by firstly touching the start marker with a pointing implement provided to the participant, moving to touch the end marker and then returning to the start marker, as illustrated in Fig. 4. Participants were asked to perform the movement cycle 15 (fifteen) times under two conditions; without iPAM attached and with iPAM attached. This was divided into 3 (three) equal sets to avoid fatigue influencing the results. The movement was designed to be both realistic and to involve all of the system's DoF such that it represents a general case. The iPAM seating system was used for both test conditions. In addition to providing a consistent seating height it allowed the use of a harness restraint to minimise movement of the trunk. This helps to maintain repeatability between tests. For the tests involving iPAM an operating protocol was devised to ensure both correct operation of the system and test repeatability. The protocol is summarised below:

1) Place iPAM in "gravity compensation" mode
2) Seat participant and fit harness restraint
3) Re-line upper-arm orthosis and attach
4) Re-line forearm orthosis and attach
5) Measure position of orthoses on upper-limb segments

Under both test conditions movement was recorded using a motion analysis system with active infra-red markers. The NDI Optotrak Certus has high accuracy (up to 0.1mm) and

TABLE I

SUMMARY INFORMATION FOR THE SUBJECTS INVOLVED IN THE IPAM PRELIMINARY TRIAL

	Sex	Age	Since Stroke (Years)	Type
P0	Male	28	N/A	N/A
P1	Female	55	2	Left CVA
P2	Male	61	1	Left CVA
P3	Male	38	1	Left CVA
P4	Female	53	1	Left CVA
P5	Male	46	3	Left CVA
P6	Male	83	1	Left CVA

TABLE II

THE VERTICAL FORCE PROVIDED BY IPAM IN EACH OF THE TEST CONDITIONS

	Upper arm	Forearm
No Lift	0N	0N
Low Lift	3N	4N
Medium Lift	6N	8N
High Lift	9N	12N

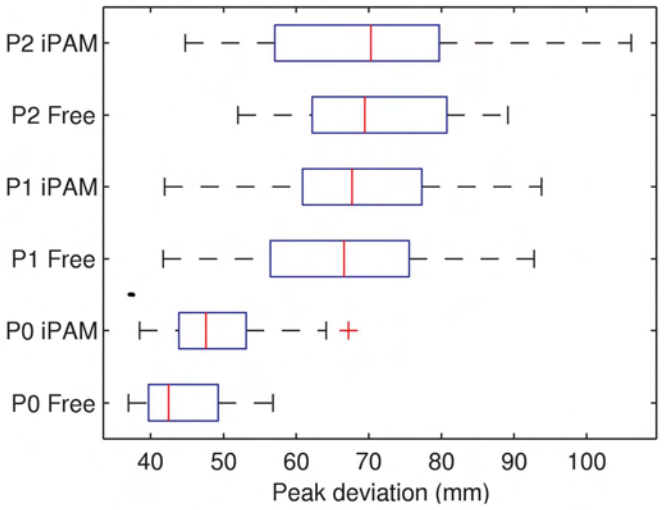


Fig. 6. Box plots for the peak deviation

is approved for use in medical environments. It was used to record the position of both markers and the pointer relative to a predefined cartesian coordinate frame. In addition, when iPAM was connected to the participant it was used to collect a range of data on orthosis and upper-limb position.

A total of 3 (three) subjects were recruited for the first experiment. A PT examined each of the subjects prior to testing to determine suitability and assess impairment. The subjects were comprised of 1 (one) healthy subject (P0) and 2 (two) patients with stroke (P1,P2) who have right hemiparesis affecting voluntary reaching movement. A summary of all the patients recruited for the trials is given in Table I.

2) Experiment 2: A modified version of Experiment 1 was designed to test the affect of adding varying levels of 'lift' to the upper-limb. A new movement was defined using only a single end marker which was located distally, just exceeding the maximum healthy reach of the participant. The start point of the movement was defined to be a comfortable rest position with the upper-limb flexed 90 degrees at the elbow. The change in movement definition was implemented to allow measurement of both the pattern and range of upper-limb movement. The full movement cycle begins at the start position, moving to the end marker and then returning to the start position.

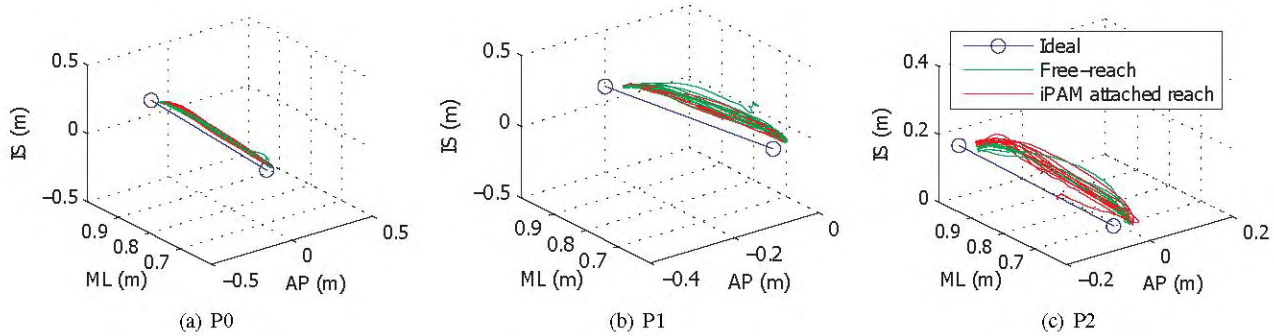
The experiment tested 4 (four) different conditions; no, low, medium and high assistance against gravity. No assistance corresponds to the standard gravity compensation mode of iPAM in which the actuators compensate for the weight of the robot. The amount of lift against gravity that each condition provides is detailed in Table II.

The same operating protocol as described for Experiment 1 was used to ensure a consistent configuration. After this initial setup the level of lift was gradually introduced by the control scheme over a period of 5 seconds to prevent sudden movement. During the introduction of the lift force, or at any time during the experiment, the participant was instructed to report any discomfort at which point the lift force would be safely removed and the robot system detached from the upper-limb. Participants were asked to begin movement shortly after the lift had been introduced. For each condition 15 (fifteen) repetitions were recorded, again divided into 3 (three) equal sets. Movement was recorded using the NDI Optotrak Certus motion tracking system and the iPAM robot system as described for Experiment 1.

A further 4 (four) subjects were recruited for the second experiment. All of the subjects had suffered from stroke (P3,P4,P5,P6), as summarised in Table I. Of the four subjects, 1 (one) was rejected (P6) because they had no functional use of the affected upper-limb, therefore to initiate and maintain any movement required active intervention from a PT. This level of impairment will be more suited to future work with the cooperative assistive controller controller [14].

C. Results

1) Experiment 1: All subjects (P0,P1,P2) completed the activities in Experiment 1 successfully, with no reports of discomfort or discontentment. Fig. 5(a) shows the resultant trajectories followed by each of the subjects. From inspection of these results, it is evident that the general trend of movement is similar between the free and robot attached movements, with no marked difference in the range, or pattern, of movement. Analysis of the results shown in Fig. 5 was performed to quantify any differences between the experiment conditions. The peak deviation from a hypothetical ideal straight-line trajectory was calculated for each movement attempt and used as a measure of movement efficiency. Fig. 6 shows the distribution of results between the two reach conditions for each subject. The results shown in Fig. 5 and Fig. 6 indicate that, when in a passive gravity compensation mode, the iPAM system does not impede upper-limb movement. This suggests that firstly, the gravity compensation mode is effective and there are no erroneous



(a) P0 (b) P1 (c) P2

Fig. 5. Free movement vs iPAM attached movement

forces applied to the upper-limb, and secondly that the combined robot-human system does not impose kinematic constraints on the upper-limb.

2) Experiment 2: All of the subjects (P3,P4,P5) selected for Experiment 2 completed the movements successfully. There were no reports of discomfort for any of the different lift levels. Fig. 7 shows representative plots of the trajectory followed by each subject, summary statistics for the full range of movements are presented in Table III.

From Fig. 7, it is apparent that the subjects had differing responses to the levels of lift provided by iPAM. Subject P3 shows no discernible difference in the range of movement, with similar movement patterns across all of the levels of lift. Conversely, subjects P4 and P5 show an increase in the distal extent of their reach as the level of lift is raised. There is also a lateral shift in the movement of P5 as lift is increased. The increase in reach of subjects P4 and P5 can be examined in further detail using upper-limb joint angle data from the iPAM system. Fig. 8 shows a cyclogram [1] of the shoulder and elbow extension of P5. It is clear that the pattern of movement, illustrated by the response slope, did not change significantly for these joints between the lift conditions. However, the range of movement in both elbow and shoulder extension are increased, explaining the increased reach in the transverse plane. It was noted from both visual inspection of the experiment and upper-limb joint data from iPAM that there was a general trend to higher shoulder abduction as the level of lift was increased. This accounts for the lateral shift of the movements in Fig. 7. The marked difference in response between subject P3 and P4-P5 highlights an interesting property of this control mode. From the PT inspection it was found that subjects P4 and P5 had a reduced range of voluntary movement in both the shoulder and elbow whilst P3 was reported to have a near full range of movement. Consequently, the additional support given to P3 could do little to improve the existing range of movement. However, for P4 and P5 the increased support clearly increased range of movement, indicating that the original deficit is likely to be a function of muscle weakness. Another feature of the increased lift is the support provided to the shoulder complex, somewhat analogous to the sling-suspension systems commonly used in rehabilitation settings.

[1]A cyclogram is a plot of two joint angles

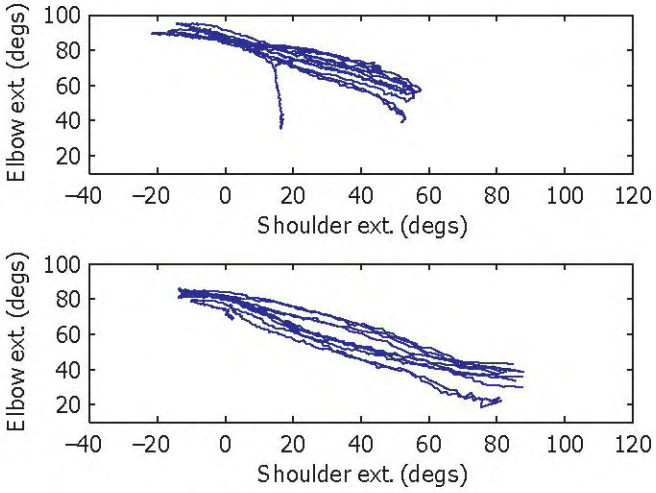


Fig. 8. Cyclogram of shoulder-elbow flexion for P5 with no lift (above) and high lift (below)

Through informal discussion the subjects expressed a general preference towards the higher levels of 'lift', particularly P3, who suffers from subluxation of the shoulder.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The iPAM dual robot system has been presented. It has been demonstrated that patterns of movement are unhindered by attachment to the robot whilst operating in gravity assist mode. This is as expected due to iPAM's ability to determine the orientation of the robot end points and alter the level of lift accordingly. The passive three DoF permitted by the orthoses designs means no undesired forces or torques are placed on the arm, and hence the patient does not feel the robot coercing the arm to a particular trajectory. The ability of the robot to accommodate a range of movement without hindering the nature in which the arm moves provides a good platform on which to build more advanced control schemes.

As noted, at this stage in iPAM's development, the system is unsuitable for patients with little to no voluntary movement as it still requires muscle activation to move the arm, however it is apparent from the second set of trials that those patients with a restricted range of motion, through use of iPAM in load compensation mode, were able to increase their overall

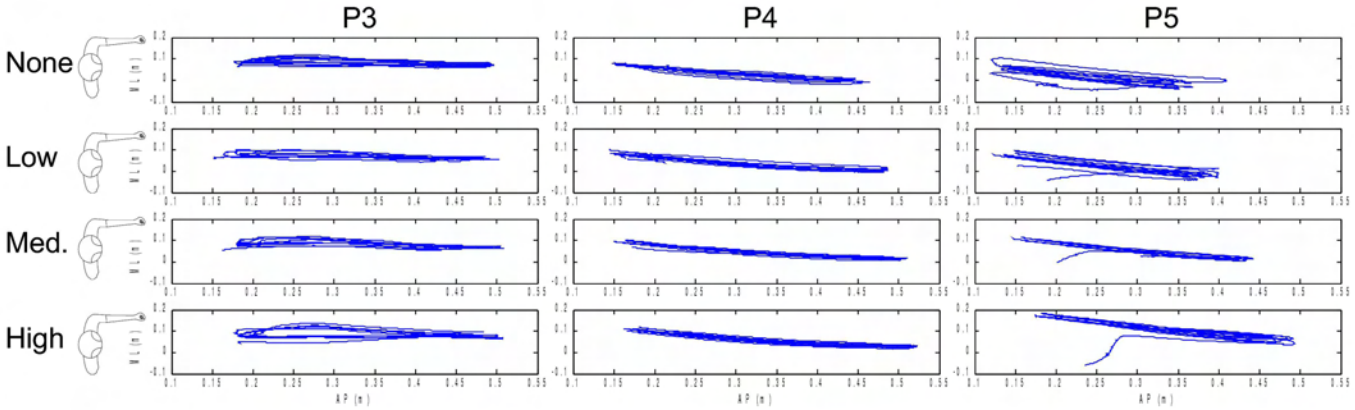


Fig. 7. Position of the hand in the transverse plane through a reaching movement with varying levels of lift provided by iPAM

TABLE III
SUMMARY STATISTICS FOR EXPERIMENT 2

		No Lift	Low Lift	Medium Lift	High Lift
P3	Mean (SD)	0.510 (0.022)	0.520 (0.031)	0.503 (0.001)	0.521 (0.034)
	% Mean change	-	102	99	102
P4	Mean (SD)	0.452 (0.030)	0.478 (0.013)	0.495 (0.011)	0.512 (0.010)
	% Mean change	-	106	110	113
P5	Mean (SD)	0.391 (0.026)	0.417 (0.024)	0.443 (0.018)	0.474 (0.015)
	% Mean change	-	107	114	121

reach by increasing the angles through which certain joints could move. While it is not likely that this will be a method through which treatment will be implemented, it has proved a useful indicator as to the overall efficacy of the system. Once the system is able to operate in an assistive mode, those patients with little to no movement will stand to benefit the greatest.

It is also apparent from the trials that not all patients will benefit from interaction with the iPAM system. Patients with a normal range of movement may still suffer movement deficits in the wrist and fingers. At present, no mechanisms for implementing wrist and finger flexion are incorporated into the iPAM system, hence iPAM may not be the best choice of treatment for these patients.

B. Further Work

Joint co-ordination control is currently being tested on the iPAM system. It has been demonstrated that the iPAM system is capable of accurately measuring the human joint angles in real-time. By utilising these measurements, we are capable of applying admittance control at each of the 6 controllable joints allowing any intervention to be tailored to the patient's specific prognosis. Once complete, it is intended that a short clinical trial will be undertaken to assess the efficacy of the iPAM system as an effective therapeutic resource.

VI. ACKNOWLEDGMENTS

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