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Effector force requirements to enable robotic systems to provide assisted exercise in people with upper limb impairment after stroke

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Abstract— **iPAM (intelligent Pneumatic Arm Movement) is a dual robotic system that aims to assist in the recovery of upper-limb movement in people with all severities of motor impairment after stroke. This paper presents effector force data gathered during the course of a pilot clinical study. It identifies the forces and workspace required to facilitate reach-retrieve exercises in a range of patients as part of rehabilitation treatments. These findings have been used in further refinements of the iPAM system.**

Keywords- robotic rehabilitation, stroke, upper limb.

I. INTRODUCTION

Dealing with the immediate and long-term consequences of stroke places a heavy burden on health services worldwide. In the UK, stroke is the most common cause of adult disability, some 150,000 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 National Health Service (NHS) over £2.8bn each year in treatment costs and £1.8bn costs through lost productivity and dependency [4]. The repercussions on the individual's ability to undertake activities of daily living (ADL) and care for themselves can be profound.

Robot-assisted exercise can supplement conventional rehabilitation treatments such as physiotherapy. By utilising robotic systems that can provide potentially therapeutic movements to patients, the physiotherapist (PT) can concentrate on more complex intervention, increasing the time individual patients spend undertaking therapeutic exercise. A number of systems have been developed internationally to deliver therapeutic exercise to the upper-limb using robot assistance. The MIT-Manus [5] is a planar robot manipulator that attaches to the distal segment of the upper limb to provide assistive movement, providing a force of up to 45N at the end effector. Additional attachments add further degrees of Freedom (DoF) at the hand and wrist. ARM-Guide [6] is a linear slide mechanism that allows straight line movement. Vertical and horizontal orientation of the path can be altered manually. These systems and several others have been investigated in clinical trials [7,8]. Overall, these studies suggest a potential for robot assisted rehabilitation but there is limited evidence of their effect on voluntary arm movement as measured by the Fugl Meyer assessment.

In order to address potential limitation of single point of contact devices, more complex systems have been developed which can more fully control the proximal and distal segments of the more severely impaired upper limb during rehabilitation exercise.

To address this issue the approach taken during the development of the iPAM system [9], involved two points of attachment utilising two custom made interactive / coordinated robotic devices to provide a portable system. The iPAM system allows delivery of expert clinician prescribed therapeutic movement trajectories which allow simultaneous active control of the upper arm and distal arm segments during reaching exercises within a 3D exercise workspace. This degree of control during active exercise would be particularly relevant in those patients who have marked weakness, low and high muscle tone as well as mechanical derangement of the shoulder such as subluxation. In essence it allows treatment of a much greater variety of upper limb problems after stroke in the context of exercises in 3D space rather than provided through control of a single distal point on the paretic limb in a single plane. Another key aspect of the iPAM system is that the effort made by the patient during the active reaching exercises can be measured and the robot assistance tailored to the patient's voluntary effort.

Approaches to control proximal and distal segments of the upper limb have also been adopted by other robot devices. The

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Pneu-WREX [10] system comprises a 5 DoF exoskeleton actuated by pneumatic cylinders. The limb is supported at upper arm and wrist and features a pressure sensitive handle for interacting with a visual display. ARMin III [11] is an exoskeleton type robot that fits around the patient’s arm allowing active control of six degrees of freedom (DoF) in the form of three rotations around the shoulder, rotation of the elbow and pronation/supination and flexion/extension at the wrist. Translation of the glenohumeral joint is mechanically coupled to arm elevation as in natural movement.

The aim of this study is to measure the effector forces that patient arms are subject to when therapeutic movements are prescribed by a physiotherapist. It identifies the forces and workspace that the robot system has to provide to control the paretic arm while facilitating reach-retrieve exercises in patients. The iPAM system is described in further detail in section II to illustrate the how the system can control proximal and distal segments of the paretic upper limb simultaneously. Section III describes the treatment provided during the pilot study and IV, the data collected. Sections V introduces the refinements to the existing iPAM system (iPAM MkII).

II. THE IPAM SYSTEM

iPAM is a dual robot rehabilitation system designed to allow control of the upper arm and forearm during reaching exercises. Each robot consists of three active pneumatically powered rotational joints that are connected to the patient’s upper limb via a passive orthosis that allows three passive rotational DoF. These allow the arm to align properly within the system. Analogous to the manner in which a PT holds a patient’s arm to facilitate movement in a paretic arm. The distal robot orthosis allows control of the movement of the patients forearm. The proximal robot orthosis is attached at the mid-point on the upper arm to control proximal arm movement in relation to distal arm movement. The iPAM system, attached to a patient, is shown in Fig. 1. The end-effector of each robot can easily be switched to provide left and right sided operation. With a total of six active DoF it is possible to control six DoF of the upper-limb (five DoF at the shoulder and one DoF at the elbow). Rotary sensors (Novotechnik) measure the rotation of the six active robot joints while two six-DoF force/torque transducers (JR3) record the relative forces between the robots and the human limb.

The design allows assisted exercises to be prescribed by a PT who records the desired trajectories by guiding the system with the patient attached through a specified therapeutic movement as judged by clinical examination (similar to routine clinical practice). These exercises are not confined to a particular plane but can be prescribed in the context of a 3D exercise workspace. This recorded movement can then be replayed in active assistance mode allowing for assisted and controlled variation in practice that takes into account the effort made by the patients during the exercise task. The prescriptions are personalised to the individual based on the clinical pattern of muscle weakness and spasticity and the level of assistance can be tailored to their ability thus incorporating the therapist’s clinical assessment into machine based exercise.

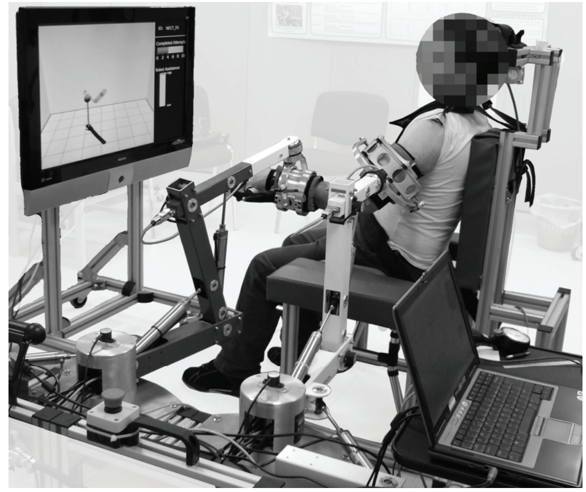

Figure 1. iPAM Mk I robot system

Several of these exercise prescriptions can be used with the patient in one therapy session and can also be repeated in subsequent sessions. Once a prescription has commenced, no further input is required from the PT. The patient is capable of stopping the system at any time via a patient-stop button which causes the robot to gently return the arm to a comfortable resting position.

A. *Human arm model*

The link between the two distal segments of the robots is the patient’s limb and therefore it is essential that the robots operate in a coordinated manner. Any misalignment or excess force could put unwanted forces and torques through the patient’s limb. In order to prevent this, a novel control scheme was developed that operates around the DoF of the human joints rather than the Cartesian endpoints of the robots. This requires an accurate model of the human limb. As there is no means of directly measuring the human joint angles, the iPAM system must estimate these from parameters known to the system. This requires a mapping from each robot's task space into a coordinate system representing the human arm. The human arm model has six DoF. They represent: shoulder girdle elevation/depression; shoulder protraction/retraction; shoulder flexion/extension; shoulder abduction/adduction; shoulder internal/external rotation; and elbow flexion/extension. Details of the upper-limb model and joint estimation technique have been previously reported [12].

B. *Robot controller*

With sufficient estimations of the human joints, it is possible to employ an admittance control scheme that operates around the six controllable human joints rather than the robot end-effectors. PID control is utilised at the six robot joints to provide the correct endpoint positions of the robot to achieve a desired upper-limb movement. The admittance function modulates the input trajectory for each human DoF as a function of measured force/torque and takes the form:

$$\delta x = F/(Kx+Cx.s) \qquad (1)$$

where K and C are stiffness and damping terms respectively. The modulated human joint angles are then used to determine the desired robot end effector positions via the forward kinematics of the arm. These are subsequently converted into desired robot joint angles using the robot's inverse kinematics.

The most significant facet of this controller is the ability to specify the assistance received by each individual degree of freedom on the arm. For instance, glenohumeral subluxation is a particular risk after stroke. During physiotherapy the integrity of the shoulder complex must be preserved by supporting the upper arm carefully. This can be replicated by specifying high levels of assistance to the shoulder's vertical translation d_1. This is not possible with a conventional Cartesian impedance controller because the arm's DoF are coupled with respect to robot task-space. Increasing assistance in the vertical axis will also impact upon shoulder extension/flexion. A detailed description of the control system has been presented previously [12].

III. ROBOT TREATMENT

A pilot investigation was undertaken involving 16 people with stroke using the iPAM system. The age range of the subjects was 41 – 81 years; the time post stroke was 4 month-12 years. The gender ratio was male to female ratio: 3:1. The ratio was a 5:3 ratio for right to left hemiparesis. Fugl-Meyer score ranged from 6 to 52 out of 60, presenting a wide range of arm impairment. Each patient had between 14 and 20 hour-long robot sessions. During each session, between 30 and 45 minutes was spent undertaking active exercise. The total number of upper limb iPAM exercises completed per participant ranged from 406 to 718.

The exercises undertaken by the participants were based on movements prescribed by a physiotherapist via the iPAM system. The PT does this by physically moving the participant's limb through a specific movement trajectory via the distal segment of the dual robots (see Fig. 2). These movements were based on a clinical assessment of the patient so as to target the particular movement deficit of the patient during iPAM assisted exercise.

Figure 2. A movement exercise being prescribed on the iPAM system by a physiotherapist using the upper and lower segments of the robots.

Two six-DoF force transducers, housed between the distal robot links and the orthoses, allow the forces applied by the PT to be recorded. These forces are in the Coordinate frame of the end effector of the robots. Six rotary sensors record the range of movement undertaken be each robot joint across all prescription. Using the robot joint angles and the forward kinematics of each robot it is possible to determine the Cartesian position of the attachment points of the human arm relative to the patient's shoulder (determined during the arm calibration). By collating this data across all the prescribed movements, it is possible to determine a desired workspace for both the distal and proximal arm segments. The force data can be converted from the robot end space into a global space, allowing the required Cartesian forces for facilitating upper-limb therapy to be found. Both these sets of data could then be used to refine the iPAM control system such that the workspace and joint force requirements can be met. User centred design was a key aspect of iPAM refinements [13].

During prescription exercises, patients are asked to relax and remain passive. The robots operate in a passive state, compensating for their own weight such that the patient/PT does not have to lift the weight of robot arms themselves. To achieve this state, the pneumatic system must be capable of being back driven. The valves act to maintain a desired pressure on each side of the pneumatic actuator to produce a force based on the robot arm orientation and robot link masses. As the system is moved by external forces, the pressures at each side of the actuator change and the valves react to maintain the pressures at the correct balance. This makes the system inherently back-driveable. The resistive load caused by the system is due to the speed with which the pneumatic system can react to changes in pressure and also the friction within the system. It was evaluated by completing a wide range of free reaching movements in the system. The resultant resistive loads caused by the system in these movements were 7.221N RMS (2.770N STD) at the upper arm orthosis and 7.635N RMS (2.842N STD) at the forearm orthosis [14]. Due to the placement of the force transducers between the patient's limb and the point at which the PT applies the forces to the system, the resistive loads outlined above do not contribute to the global force data presented in this paper.

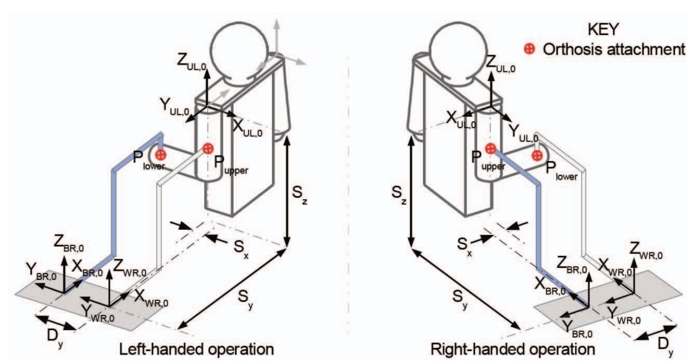

Figure 3. iPAM robot co-ordinate system.

IV. DATA GATHERED

Data were gathered from 156 individual PT prescribed exercises across the 16 patients involved in the study. Each patient had 6-11 personalised exercise tasks prescribed over the course of the intervention period. Data presented are based on the global co-ordinate frame (see UL,0 axis in Fig. 3) around a reference shoulder position (determined when the patient arm is calibrated within the system). The data gathered represents the forces and positions delivered by the PT during the recording of prescription tasks, there is no contribution from the robot itself as it operates in a passive mode.

Histograms of the positions of the lower and upper orthoses through the entirety of the prescribed movements are presented in Fig. 4 and 5 respectively. The force data for the same attachment points are shown in Fig. 6 and 7. Table 1 presents the key values from the data collected.

Results show that that the lower arm workspace can be equated to a cube of 0.451m in the X axis (anteroposterior), 0.459m in the Y axis (mediolateral) and 0.535m in the Z axis (superior/inferior) and an upper arm workspace of 0.277m in the X axis, 0.182m in the Y axis and 0.248m in the Z axis. As expected the upper orthosis workspace is far smaller in volume than that required at the lower orthosis. However, if a system must be suitable for left and right sided operation, then both robots must be capable of the permitting both the lower and upper arm workspace. The resulting reach area demonstrates a large active workspace for patients to use when undertaking exercise in the iPAM system. The workspace used by the therapist for reach-retrieve movements was not limited by the iPAM system. The original workspace was determined with the help of several PT's [15].

Fig. 6 and Fig. 7 show the force in the Z axis as primarily positive at both attachments. This it to be expected as the PT is predominantly required to lift the arm during facilitation. Likewise the force in the X axis has a negative bias due the force required to extend the shoulder and elbow.

From Fig. 7 is can be seen that there is a trend towards a negative force in the Y axis of the upper arm attachment. It is common for patients with weakness at the shoulder to use a pattern of abduction and medial rotation of the shoulder rather than shoulder flexion when attempting forward reach. To correct this movement pattern, a PT will provide assistance to maintain the correct alignment of the arm, resulting in a lateral force at the upper-arm opposing the abduction. This again highlights the benefit of a dual point of attachment, allowing the correction of this abnormal movement pattern.

While the results are shown for the upper and lower arm separately, the system must be suitable for both left and right sided operation and hence each robot arm must be capable of providing the peak forces and range of movement across each attachment.

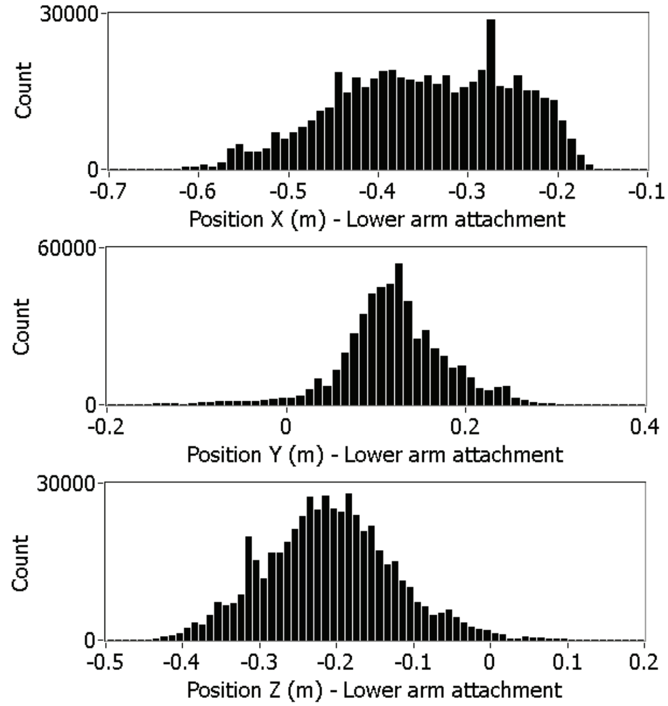

Figure 4. Histogram of position data for the lower attachment.

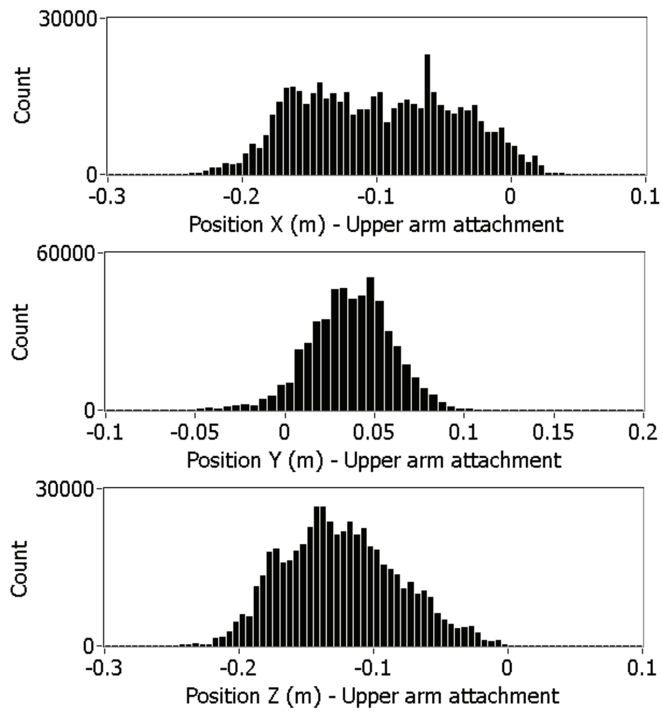

Figure 5. A Histogram of position data for the upper arm attachment.

Table I

	Min			Max			Range			Mean (std)		
Variable	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Position lower (m)	-0.613	-0.153	-0.433	-0.162	0.306	0.102	0.451	0.459	0.535	-0.35 (0.095)	0.12 (0.058)	-0.21 (0.083)
Position upper (m)	-0.239	-0.052	-0.244	0.038	0.130	0.004	0.277	0.182	0.248	-0.10 (0.057)	0.04 (0.022)	-0.12 (0.042)
Force lower (N)	-46.0	-11.2	-9.4	20.3	35.8	35.2	n/a	n/a	n/a	-2.48 (9.00)	2.34 (5.16)	13.26 (6.07)
Force upper (N)	-35.8	-42.8	-22.4	21.2	16.0	34.5	n/a	n/a	n/a	-2.47 (6.21)	-9.18 (7.29)	4.31 (7.75)

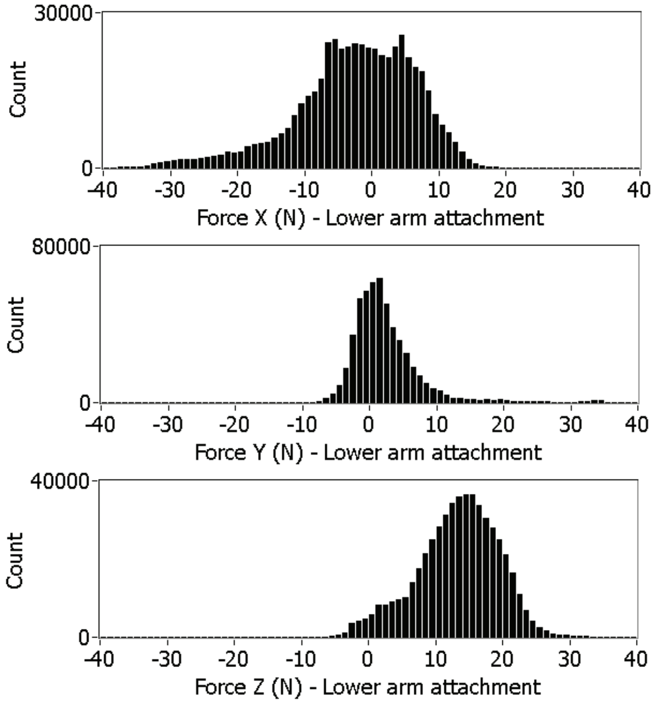

Figure 6. A Histogram of force data for the lower-arm attachment.

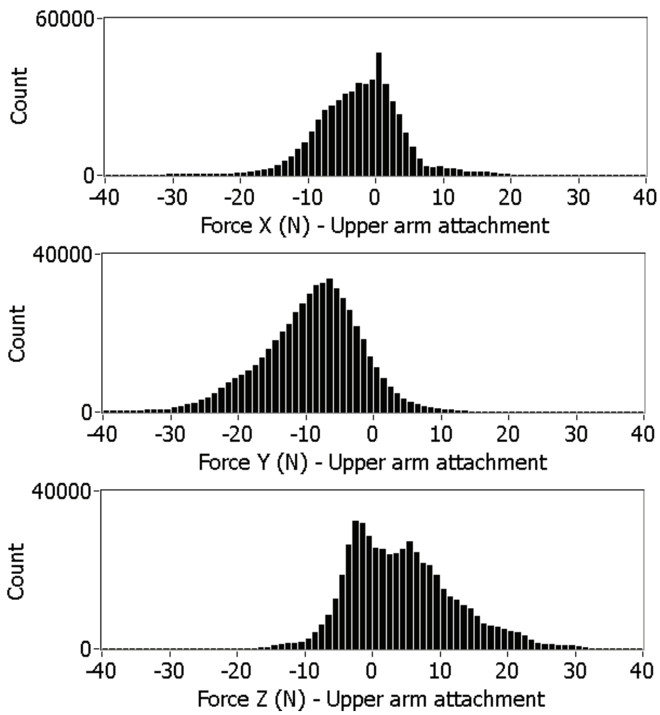

Figure 7. A Histogram of force data for the upper arm attachment

Using the force and position data it is possible to use the static components of the Recursive Newton Euler equations to determine the required torques at each robot joint (due to the relatively slow movement of the therapy exercises, the dynamic components are negligible). The corresponding robot joint angles can also be determined using the robot's inverse kinematics to determine the correct sizing and positioning of the pneumatic actuators used in the iPAM system.

This same data set was also analysed in terms of the six DoF human joint model, providing the required forces/torques and displacements/rotations at each individual human joint to facilitate these prescribed exercises and is presented in [14].

V. Development Of iPAM Mk II

Using the results presented above and the qualitative results gathered from patients during and after the pilot study, the iPAM Mk I system has been refined. Again, user involvement has been essential during this process. Several sessions have taken place where both patients and therapists have been invited in to assess aspects of the system as it has been developed. This feedback has then been incorporated into the design.

iPAM Mk II utilises pneumatics to actuate the system, however a refinement to the valves and cylinders have been implemented to improve the performance and reliability of the system. This will also have the effect of increasing the transparency of the system. Actuation of the base joint is now hidden from the patient within the base unit of the robot. This prevents accidental damage to the cylinders and also reduces the overall width of the system. With the orthoses unattached, it is possible to fit the robot base unit through a standard width single door, improving the portability of the system.

The orthoses have been redesigned to allow easier attachment of the patients in the system and a wider range of movement. An issue identified during the pilot investigation was that when the system was used by a patient with shorter limb segments, there was an increased chance that the upper and lower orthosis could clash when exercises were focused close to the patient's trunk. A cantilever design reduces the bulk at the front of the upper orthosis resulting in an increased range of elbow flexion. A similar design was implemented on the lower orthosis. This will allow the therapist to include hand to mouth exercises within the robot prescription (within the workspace ranges evaluated above).

Feedback from patients regarding the appearance and comfort of the patient chair indicated that the original seating system needed to be revised. This has been redesigned to provide a more integrated appearance with the rest of the iPAM system. An adapted wheelchair has been used that allows easy switching from left to right-sided operation. The standard wheel chair back rest has been replaced with a custom made frame and padded back support so as to allow free movement of the upper arm during exercise while still providing lateral trunk support. A docking station for the patient chair ensures the patient is always positioned correctly relative to the iPAM system. The refined iPAM Mk II system is shown in Fig 8.

VI. Conclusion

This paper presents both force and range of motion data gathered from physiotherapist prescribed movements during a pilot clinical trial of the upper-limb physiotherapy robot iPAM. The data collected covers patients with a broad range of movement deficits as a result of stroke and hence gives good guidance regarding the range of motion and forces required from any upper limb physiotherapy robot system and as such could be of benefit to other designers of robotic systems for upper-limb physiotherapy.

Examination of the maximum and minimum forces applied at both the upper and lower orthosis positions show them to be broadly comparable. This indicates that while prescribing therapeutic exercise movements, physiotherapists require the ability to apply forces at both upper and lower arm positions to generate the desired coordinated movement pattern. In particular, the trend seen towards a negative force in the Y axis of the upper arm attachment as a result of the physiotherapists desire to prevent abnormal patterns of abduction and medial rotation during reaching, highlights the need for multiple points of attachment.

Figure 8. The iPAM Mk II robotic rehabilitation system.

The force and range of motion data was used in conjunction with data gathered from user group feedback sessions to inform the development of the iPAM Mk II system which has been introduced. A number of refined iPAM MkII systems are currently being built for used in further clinical trials.

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