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Dual robot system for upper limb rehabilitation after stroke: the design process

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Abstract: Stroke is the most common cause of severe disability in the UK. Arm impairment is common and recovery is partly dependent on the intensity and frequency of rehabilitation intervention. However, physical therapy resources are often limited, so methods of supplementing traditional physiotherapy are essential. Robot assisted physiotherapy is one way to increase the duration patients spend participating in rehabilitation activities.

A single robot system has been developed at the University of Leeds that actively assists patients undertaking therapeutic movements in a three-dimensional workspace. However, using only a single point of contact at the wrist to assist with therapeutic reaching movements does not allow control or support of the more proximal joints of the upper limb. This could lead to discomfort during assisted exercise. In addition, the design suffers from a restrictive workspace, limiting the range of therapeutic exercise that can be undertaken. To address these limitations, the intelligent Pneumatic Arm Movement system has been developed.

A major aspect of the development process has been the continual involvement of physiotherapists and stroke patients; the end users of the system. Through inclusion of these stakeholders, a system has been developed that satisfies their requirements for workspace, comfort, safety and ease of use.

Keywords: robotic, rehabilitation, design, user involvement, stroke, upper limb, stakeholder analysis

1 INTRODUCTION

This paper presents the design process of a dual robot system for use in the rehabilitation of people with stroke. The proposed dual robot system will provide responsive coordinated active assistance of upper arm and forearm to facilitate the patient's reaching movements.

Many systems designed by engineers for medical use lack formal involvement of potential users of the system at the inception of the proposed device. Involvement of people with stroke and health care professionals during the design process increases the likelihood that the system will be successfully adopted when complete. To facilitate this, a Rehabilitation Technologies User Group (RTUG) was set up in Leeds to inform all stages of the system's development. Stakeholder input was managed by decomposing the system into twosub systems based on the user

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input required in their evaluation. The work presented demonstrates the benefits of end-user involvement in the design process, particularly, in an area where successful human–system interaction is critical.

Section 2 gives background about stroke and robot assisted rehabilitation, a summary of the prototype single robot system developed at the University of Leeds and the process of user involvement. Section 3 presents the process used to develop the intelligent Pneumatic Arm Movement (iPAM) system. Section 4 describes preliminary system-level validation of iPAM against the key stakeholder requirements.

2 BACKGROUND

2.1 Stroke and robot-aided rehabilitation

Stroke is the most common cause of severe disability in the UK, some 300 000 people are affected at any one time and up to 85 per cent of people experience varying degrees of arm paresis at onset [**1**]. Even after five years, at least 25 per cent of stroke survivors report continued difficulty using their paretic arm [**2**] resulting in long-term dependency. In addition, those who survive stroke may be left with a wide range of cognitive and emotional sequelae depending on the location of the brain injury [**3**]. This places a large burden on the National Health Service (NHS). Rehabilitation following stroke aims to maximize patients' independence. Motor learning is a process associated with practice, which leads to a relatively permanent change in ability. Studies show that increasing the level of physical therapy can improve some aspects of motor recovery [**4**, **5**], however, physical therapy resource is limited. As a consequence, the level of intervention is often inadequate in terms of intensity and frequency, with patients spending only a small part of each day in rehabilitation activities [**6**].

Robot assisted exercise can supplement traditional physical therapy. In this way, a physiotherapist (PT) can prescribe a series of simple movement trajectories to be undertaken via a robotic system allowing the PT to concentrate on more complex intervention. This has the potential to increase the time that patients spend undertaking rehabilitation activities.

Research efforts to develop robot-aided physical therapy have seen a significant increase over the past 20 years, with many groups focusing on the rehabilitation of the upper limb. A proof of concept single-armed robot system was developed at Leeds to test the feasibility of robot-assisted single degree of freedom (DOF) elbow flexion/extension exercises [**7**]. This was the first published demonstration of the impact of responsive robot assisted exercises on arm movement. Several researcher groups have since demonstrated the potential benefits of such techniques in stroke rehabilitation. Table 1 presents a number of the systems developed or undergoing development internationally.

MIT-Manus was one of the first systems to be developed. Available commercially as the InMotion[2] system, it has been used predominantly as a research tool. Clinical trials of this device have shown that improvements in motor impairment can occur. A clinical trial with 27 chronic stroke patients undertaking an intensive 3 week intervention, demonstrated positive improvements in motor impairment score, however, no comparison group was used to compare improvements observed [**20**]. The ACT^{3D} system utilizes a HapticMaster to actively reduce the forces due to gravity on the patient's arm. Results from a single case design experiment shows [**21**] that as forces due to gravity are compensated for, the range of voluntary upper limb movement increases. The UECM robotic system provides 2 DoF planar movement of the distal segment. A clinical trial of 23 patients showed the majority experienced improvement in motor function using the Fugl-Meyer assessment score [**22**].

In all the above systems, a robot interacts with the patient through a single distal point of attachment on the lower arm using an orthosis. Arm exercises are defined in terms of the robot single end-effector in *XYZ* Cartesian space. The magnitude of assistance can be varied by impedance/admittance control schemes [**23**] that operate in the robot task-space.

The use of a single attachment point has a number of limitations. By providing only one point of attachment near the wrist, the arm is under-constrained; an end-effector position can be the result of a number of different elbow and shoulder rotations. Conventional physiotherapy involves the physiotherapist using two contact points on the patient's arm: one close to the wrist to facilitate the movement of the forearm, wrist and hand, and one on the upper arm to facilitate shoulder and elbow alignment and movement. The PT does not hold the arm at a distal point and 'pull' it along the desired trajectory. For example in a patient with upper limb spasticity whose arm is being moved by a robot through a single distal point of contact, inappropriate traction forces at the shoulder may occur and cause pain. With the PT's two hands, the patient's arm is guided through a series of coordinated movements (while the patient's limb is being supported). The lack of a second contact point at the upper arm results in an under-constrained system, limiting the patient's ability to re-learn appropriate patterns of coordination between the DoFs of the involved joints.

Recently a number of devices have been developed to address some of these issues. The Pneu-WREX system comprises a 5 DoF exoskeleton actuated by pneumatic cylinders. The ARMin project features another exoskeleton-based design. Currently it features four

Table 1 Various systems for providing assistive upper-limb rehabilitation exercise

Institute	System	Type	Brief details
Northwestern University, Chicago, USA	Arm Coordination Training three-dimensional (ACT^{3D})	Single point of attachment	HapticMaster providing 3 DoF, with single point of attachment at wrist. In paper, planar motion is used with 3rd DoF altering the apparent weight of the arm [**8**]
Northwestern University, Chicago, USA	ARM-Guide (Assisted Rehabilitation and Measurement)	Single point of attachment	Linear slide mechanism allows straight line movement. Vertical and horizontal orientation of the path can be altered manually [**9**]
MIT/Interactive Motion Technologies inc., Cambridge, USA	MIT-Manus/InMotion^2	Single point of attachment	2 DoF planar motion. An additional wrist add on (InMotion^3) allows as addition 3 DoF to be controlled at the wrist [**10**]
Stanford University, Palo Alto, USA	MIME	Bi-manual system	2 DoF planar motion but there is an ability to alter the angle of the plane. Systems can use unaffected arm for bi-manual training [**11**]
University of California, Urvine, USA	Pneu-WREX (Pneumatic-Wilmington Robotic EXoskeleton)	Exoskeleton	5 DoF. Four at shoulder and one at elbow. Supported at upper arm, wrist and with a pressure sensitive handle [**12**]
Arizona State University, Phoenix, USA	RUPERT (Robotic UPper Extremity Repetitive Therapy device)	Exoskeleton	Wearable exoskeleton, 4 DOF using pneumatic muscles. 1 DoF at shoulder, one at elbow, one at forearm and one at wrist [**13**]
ETH, Zurich, Switzerland	ARMin.	Exoskeleton	4 active DoF in the form of three rotations around the shoulder and then rotation of the elbow. Passive shoulder translation permitted [**14**]
University of Reading, Reading, UK	Gentle/s	Single point of attachment	Modified HapticMaster provides three-dimensional workspace at wrist. Upper arm support using a passive suspension system [**15**]
University of Padova, Padova, Italy	NeReBot (NEuro-REhabilitation roBOT)	Single point of attachment	NeReBot provide movement in a three-dimensional work-space. Patients arm fixed to a splint driven by three wires controlling height and orientation. Three linkages alter position [**16**]
BUTE, Budapest, Hungary	Reharob	Dual points of attachment	Uses two 6 DoF robots. Upper and lower arm attachments [**17**]
Tsinghua University, Beijing, China	Upper Extremity Compound Movements (UECM) robot	Single point of attachment	2 DoF planar motion but there is an ability to alter the height of this plane. Wrist/hand attachment and passive sling mechanism to support upper arm [**18**]
Harbin University, Harbin, China	Rehabilitation robot arm	Exoskeleton	5 DoF. Two at shoulder, one at elbow, one giving pro/supination of lower arm and one giving wrist flexion and extension [**19**]

wire driven DoF and two passive DoF. Both systems have the ability to support better the patients arm throughout movements. In addition, the exoskeleton design provides the opportunity to control the arms orientation where the DoF are active. Reharob is a robotic system using two industrial robots (one ceiling, one floor mounted). Though technologically advanced and capable of coordinated manipulation of the upper and lower arm, the robots are complex and expensive. These robots require permanent fixture, and, therefore, cannot be flexibly deployed.

iPAM takes a similar approach with dual robots for upper and lower arm attachment. In order to maximize the use of the system in routine clinical environments, iPAM will have a small footprint, be easy to use on both the right and left arms of people with stroke, be affordable to health service providers and be relatively mobile to allow it to be flexibly deployed within a physiotherapy department.

2.2 Single point of contact robot prototype

A single-armed robot system, previously developed at Leeds, provides the foundation for the work presented here. The system is capable of providing assistive movement to a patient's arm in a three-dimensional workspace. It utilizes anti-stiction pneumatic cylinders to provide actuation at three revolute joints, while an orthosis allowing three passive rotational DoF is used to interface with the patient's lower arm, ensuring the orientation of the arm remains comfortable (Fig. 1).

Fig. 1 Single point of contact prototype robot system

Joint-space PID controllers were used in conjunction with a task-space multi-degree of freedom impedance controller [**24**]. This enables the robot to smoothly offer assistance to a patient when they are unable to follow trajectories independently.

The proof of concept system, while capable of providing some assistive physiotherapy exercise, suffers from the limitations outlined in section 2.1 regarding single point of attachment robots. A second limitation of the system is a result of the kinematic arrangement of the robot. The position of the actuators limits the angles through which each joint can rotate, in turn, limiting the range of therapeutic exercises. The iPAM system was designed to address these problems.

2.3 Involving users in design

Involving users in technology design processes has received increasing interest over recent years. This is as true as much for health technologies as it is for consumer products [**25**]. The National Health Service (NHS) through INVOLVE [**26**] emphasizes the importance of user involvement in research design. This ensures that research focuses on areas important to the health and wellbeing of the nation and not just driven by academic curiosity. User involvement is much more than individuals just being the subject of experimentation. For example, users should be actively engaged in generating and prioritizing areas for research, providing feedback on individual research projects, being involved in disseminating the results of research.

In the context of rehabilitation devices, the term 'users' covers both staff responsible for operating the devices, and the patients who are treated with the device. If the needs of these 'users' are to be satisfied through design, then they must be reflected in the initial brief, and in the evaluation process. A variety of design methods are available for engaging users in technology development [**27**]. Some of these methods, such as cognitive engineering [**28**] and task analysis [**29**] have been applied in the evaluation of medical devices. However, these have generally focussed on the needs of medical staff using the device (for example to minimize errors, improve patient safety). Feedback from patients is normally gathered by standardized questionnaires and semi structured interviews – either for gathering initial data to inform requirements [**30**, **31**], or for gathering feedback on design proposals and prototypes [**32**]. In the development of healthcare devices, users are often only consulted once development is complete, or near-final prototypes have been developed [**33**, **34**] to validate user acceptance. Martin *et al.* [**35**] argue that healthcare engineers are not yet as advanced as engineers in other fields at incorporating user views into their research. As development of a system progresses, changes get more difficult and more expensive to make, limiting the action that can be taken on user feedback in the later stages. Accordingly, the project reported here has placed an emphasis on involving users (both patients and therapists) *throughout* the development process, and not merely at the very beginning (to gather requirements) or the very end (to test satisfaction). The following sections describe how these users have been engaged in the development of the iPAM system.

3 SYSTEM DEVELOPMENT

Limitations described in section 2.2 of the existing single robot systems are being addressed through the development of a cooperative dual robot system which can provide controlled assistance of upper limb movement throughout a greater range of therapeutic movement. The robot system comprises two co-operating pneumatically driven robots, intrinsically linked to form an interactive robotic system which senses voluntary efforts made by the patient, supports and guides the upper arm and forearm movement of the paretic limb to provide the type of coordinated motion commonly prescribed by physical therapists. By this means, mechanical complexity, size, weight, space usage and hence costs are minimized. The approach can be likened to the PT's two hands, gently guiding the patient's arm through a series of motions. The use of two robots working as one system while attached to a human arm presents considerable engineering challenges. While the movement range of the upper arm is comparatively small compared to that required at the wrist (hand), utilizing physically similar robot arms for both attachment points has a number of advantages.

1. Production costs can be reduced as manufacturing requires only one type of robot arm.
2. Mechanically similar robot arms can easily be 'reversed' to accommodate exercises on the left and right arm.
3. Need to develop only one type of joint position controller as each robot arm will be identical.

An important consideration in technological developments of this nature is the man–machine interface. The development of the 'upper arm and forearm orthoses' requires considerable input from both patients and physical therapists. Upper and lower arm orthoses have different requirements determined by the relative positioning of the attachment points with respect to the body.

This section presents the process used to develop the system, and the methods used to engage patients and health professionals in its development.

3.1 System development process

The guiding philosophy of the development process was to involve patients and therapists throughout, to ensure their needs were met. To manage this, the system was decomposed into two subsystems, based on the stakeholder involvement required in their evaluation. The *Robot Arms* relate to the therapeutic requirements of the system, particularly, its workspace, and therefore, required input from therapists. As well as the design of the arms themselves, their relative positioning also needed to be optimized. The *Orthoses*, which attach the robot to the patient, relate to requirements such as comfort, safety, and ease of attachment, and therefore, required input from both patients and therapists. The two systems were developed in parallel, using a process similar to Boehm's risk-based Spiral Model of systems development [**36**]. This involved testing and refining progressively more detailed prototypes with input from the relevant stakeholders. Once the design of the subsystems was complete, they had to be integrated and validated against the system requirements as a whole, an approach similar to the Vee Model of systems engineering proposed by Forsberg and Mooz [**37**]. Figure 2 provides a flowchart of the design process. Clearly the eventual cost of the device is an important consideration in the design process. If the equipment is too expensive it will not be taken up readily by cash strapped health care providers. Therefore value-engineering concepts underpinned every stage of iPAM development. The rest of this section outlines the iterative design of the robot arms, their positioning and the orthoses, while section 4 discusses the validation of the system as a whole.

3.2 Design of robot arm

There were three options for enlarging the workspace of the single robot system: to increase the link lengths, increase the angle range of the joints or alter the configuration of the robot entirely. The simplest solution was to focus efforts on the existing configuration. Using the computational kinematic arm model, parameters were chosen to describe the range of movements between the rest position shown and the functional and therapeutic maximum reach to either side of the patient's midline. To construct this model, the range of desired arm movement during therapy was obtained using motion analysis equipment. Expert neurological physiotherapists guided the subject's arm through the range of therapeutic exercises. The input from PTs was essential to ensure that the final design had the desired therapeutic workspace. The resultant lower-arm workspace, and its orientation relative to the patient's body, is presented in Fig. 3. This fully encompasses the movements obtained in the motion capture data. The desired workspace can be approximated to the black wire-frame cuboid shown.

The workspace visualization is useful not just in comparison and assessment, but also in optimization. Through an iterative process, small changes were made to the kinematic parameters of the single robot arm to ascertain their contribution to the workspace. This determined that the main limiting factor for the restricted workspace was the narrow ranges of movement at the robot arm joints and to a lesser extent the robot arm actuator position. A second iterative process was used to modify the kinematic parameters of the robot arm to achieve a workspace comparable to that desired. The original single robot workspace volume is shown in Fig. 4(a). By increasing the final two link lengths by 0.1 m and increasing the angle range at all joints to $\pm 30^\circ$ the optimized workspace shown in Fig. 4(b) was produced. The robot covers the majority of the desired therapeutic workspace. There were only small regions at the extremes of therapeutic upper limb movement which fell outside the limits of the dual robot system. These 'mismatched' regions are unavoidable due to the robots kinematic configuration of three revolute joints.

Further extension of joint ranges was limited by the actuators, which are a core part of the robot design. In addition, the robot arm link lengths were constrained by the overall bulk of the robot and the actuators. The positions of the pneumatic actuators were altered to accommodate the increased joint ranges and link lengths. The resultant design provides a workspace that encompasses the majority of the desired workspace defined through stakeholder interaction while remaining mechanically practical.

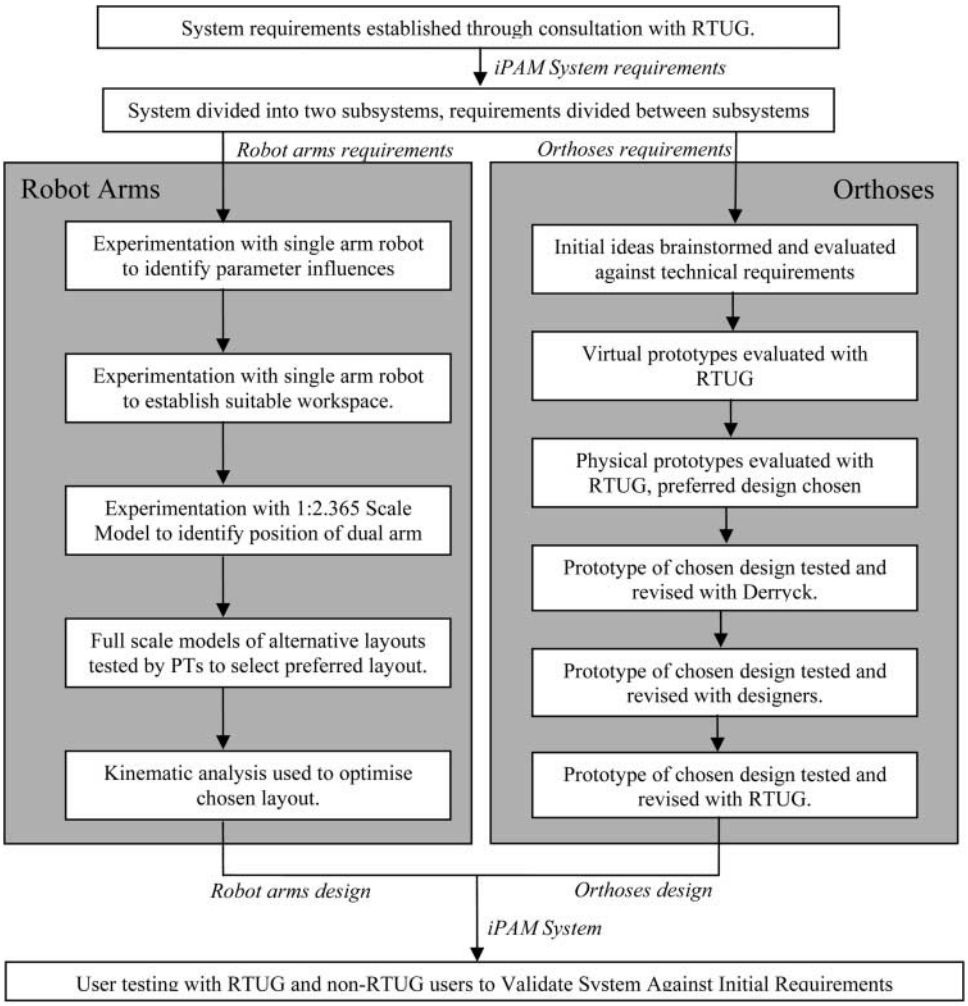

Fig. 2 Flow chart of iPAM development process

Designs for the robot arm components were based on those used on the single prototype robot described in section 2.2. Finite-element analysis was conducted on the components of the robot arms to test structural integrity. As a result of user feedback concerning the physical appearance of the single prototype robot system, a protruded polyester resin box section was used for the robot arm components to allow cabling and air lines to be hidden inside the robot system.

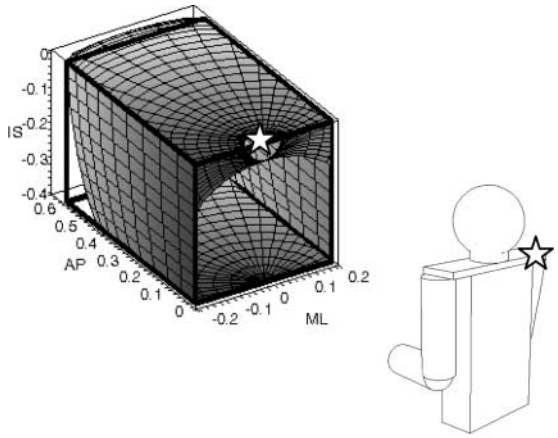

Fig. 3 Lower-arm workspace (☆ demonstrates the position of the shoulder in the workspace)

3.3 Optimizing position of robot arms

An important aspect of the design process is to ensure that the two robot arms are positioned so that they allow easy attachment to the patient and do not obstruct the PT access to the patient's arm while the robot is attached to it. Initially a 1 : 2.4 scale model was produced to help determine the optimal positions of the robots relative to each other and with respect to the PT and patient (Fig. 5a). In order to determine the range of exercises that are deemed to be therapeutically suitable for any individual patient the PT needs to guide the patient arm through the desired movement while the patient's arm is attached to the robot. Therefore it is essential that the PT can comfortably and effectively provide

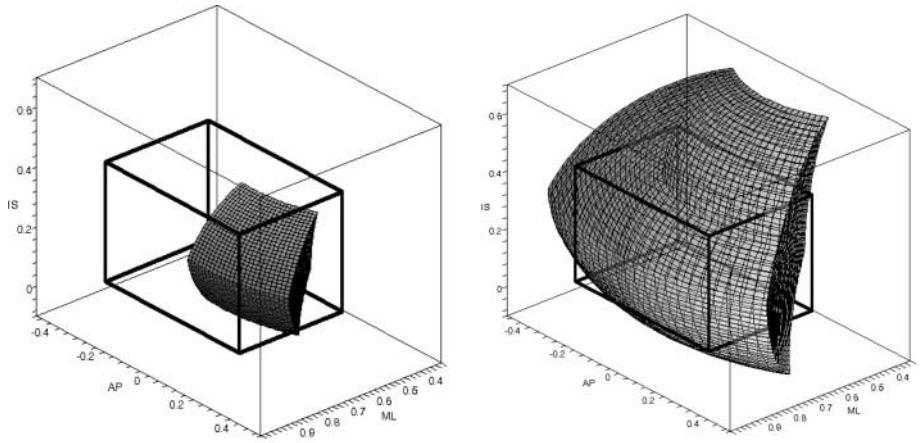

Fig. 4 (a) original and (b) optimized robot workspace

Fig. 5 Physical models used for iPAM development: (a) small scale mock-up; (b) full size mock-up; and (c) visual Nastran simulation

assistance to the patient during the initial trajectory recording stage which involves holding the distal segments of the robot links and moving them throughout the workspace. In addition to the kinematic data, using 6 DoF force transducers positioned between the patient and the PT, the robot system will also measure the forces that the physiotherapist uses to move the patients arm. These sensors are positioned so as to not to impede PT access.

Second stage of the process involved building a full size physical model (Fig. 5b). PTs were invited to test two possible positions: one with the two robots parallel to each other with the PT situated behind the patient; the second with the upper robot at 45° to the lower one with the PT between the robots to the side of the patient. The difficulty of providing the movement in the latter of these two configurations was evident and so the parallel robot system was selected and implemented in the simulation software (Fig. 5(c)).

This also provided an opportunity to investigate the position and orientation of the orthoses used to attach the patient to the robot system. In order to allow easy switching between therapies directed at either the left or right arm, both robot bases were designed to be fixed at the same height. Given the anthropometric constraints it was necessary to have different orthotic designs for upper arm and forearm attachment points. The end-effectors of each robot would therefore have to be switched depending on which arm was being treated. Kinematic analysis determined that the upper arm orthosis would be required to run in line with the 3rd link of the robot, while the forearm orthosis would need to be positioned approximately 15 cm below the end of the robot controlling the forearm. These were incorporated into the end-effector designs.

3.4 Design of orthoses

The orthoses provide the interface between the robot arms and the patient. Their design incorporated opinions of people with stroke, physiotherapists,

doctors and engineers. In addition to the technical requirements, issues such as comfort, ease of attachment and safety are important. To better understand the context of use, the designers accompanied physiotherapists on clinical visits, so that they could directly observe the practical difficulties posed by the variety of arm impairments in people with stroke, to hear their views and identify their preferences. Eight key issues were identified:

(a) need to fit a range of arm sizes from 5th percentile female to 95th percentile male;
(b) should not impede range of motion typically used in physical therapy treatments;
(c) ease of attaching the orthoses;
(d) safety and comfort of the patient and physiotherapist during use;
(e) single-patient-use skin contact material for infection control;
(f) affordability for the initial purchase and long-term maintenance;
(g) must allow three rotational DoF around the centre of the human forearm;
(h) orthoses must be light and be able to transmit forces up to 240 N.

As iPAM requires both the upper arm and forearm orthoses, both were developed in parallel. The greatest challenge in designing the orthoses was addressing the issues of comfort and ease of attachment, which could only be properly evaluated through user testing with prototype devices. The initial design incorporated the technical requirements, which were tested with users and revised based on their feedback. The Rehabilitation Technology User Group (RTUG), which included people with stroke, their families and physiotherapists provided crucial input to the design process.

A range of solution principles for the functions of the orthoses were brainstormed using sketches, and narrowed down to two promising ideas based on the technical requirements. These were developed and dimensioned on the I-DEAS CAD system using finite-element analysis and anthropometric data to help select appropriate dimensions and materials. Before investing in physical prototypes these ideas were presented to RTUG as virtual prototypes, to get initial feedback and make appropriate alterations to the CAD. Physical prototypes were developed from the virtual prototypes using an iterative process, with three stages of testing.

The first stage of testing was to ensure the prototype met the technical requirements, i.e. it could perform the required motions and be robust enough to safely withstand normal use and likely user errors. A mechanical model of the human arm, 'Derryck', was also used to test the suitability of orthoses [**38**]. The subjective requirements of comfort and ease of use were the foci of the second and third stages of testing.

Fig. 6 iPAM system with upper arm and forearm orthoses

The second stage involved the designers trying the orthoses out on themselves to fine-tuning the physical design. This was important, as time with the User Group is limited, and is better concentrated on providing new insights rather than correcting obvious problems that were readily identified by team members.

Once the team felt that they had a suitable design, testing moved on to the third stage: presenting the orthoses to the RTUG for trial use. This involved the physiotherapists and patients carrying out the type of arm exercises that might be undertaken within a real treatment session. With a physical prototype to interact with, the discussion and feedback from the RTUG was more animated and productive than it been with the virtual prototypes. Their views on the comfort, safety and ease of using each design were gathered through questionnaires. Based upon this feedback, the preferred design was selected, and some modifications were made, to arrive at the finished versions of the orthoses, which could be attached to iPAM for the final evaluation (Fig. 6). Both orthoses allow three rotational DoF through segment centre.

4 VALIDATION OF DESIGN

Although user input played an important role throughout the development of the subsystems, it was important that the system as a whole was tested to validate its performance against the key requirements. Although it is essential that the robot design is mechanically and electrically capable of meeting the specified performance, the system has to be directly linked to human subjects. If iPAM does not feel safe and comfortable, it is unlikely that patients will be willing to utilize the system as part of a rehabilitation treatment program, regardless of its performance.

This section presents an objective validation of the dual robot design against its physical requirements and subjective assessments of the system against the requirements of comfort, safety and ease of use.

4.1 Physical validation

4.1.1 XYZ Cartesian position and workspace validation

The ability of the robot to sense its position in the therapeutic workspace is essential for robust control of the system and also to determine the human joint angles. In order for the system to accurately estimate the position of the patient's arm, it is necessary that the position of the end effector of each robot is known.

The Optotrak® Certus™ is a high-speed active optical tracking system that is capable of tracking the position of electronic markers to an accuracy of ± 0.1 mm. Optotrak® was used to provide the end point position in three-dimensional space. Both robot arms were moved through a range of trajectories. The end-effector position in Cartesian space was measured both by Optotrak® and through the forward kinematics of iPAM using calibrated joint signals. Figure 7 shows the comparison between iPAM's calculated position and the actual position, as measured with Optotrak®. All displacements are relative to the base joint.

iPAM's sensors allowed the end position to be tracked to an accuracy of ± 5 mm. This analysis confirms the accuracy of the end position identified by iPAM's sensors when compared independently with the Optotrak® system. Compliance within the robot links is deemed as the main contributing factor to the error margins.

During iPAM's development the desired workspace necessary for therapeutic arm exercises was determined by experienced neurological physiotherapists. Figure 8 shows the original specified workspace with the superimposed actual workspace measured using Optotrak®. It can be seen that iPAM can fully meet the specified range of movement outlined in section 3.2.

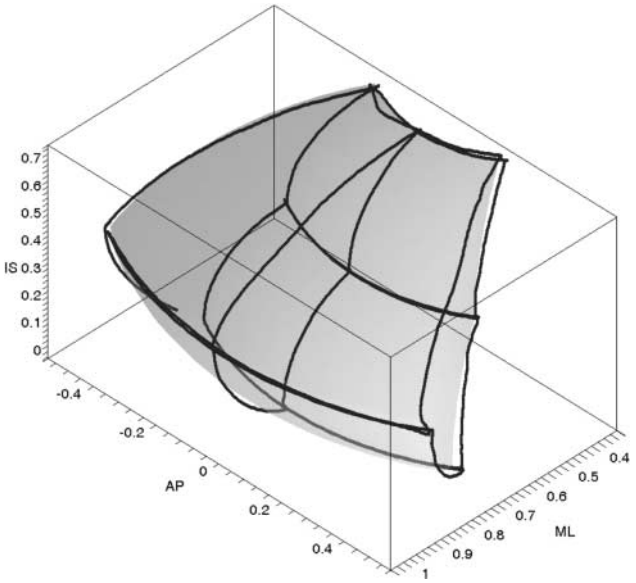

Fig. 8 Specified workspace compared to actual workspace. Shaded area represents desired workspace. Black lines show the range measured with Optotrak®

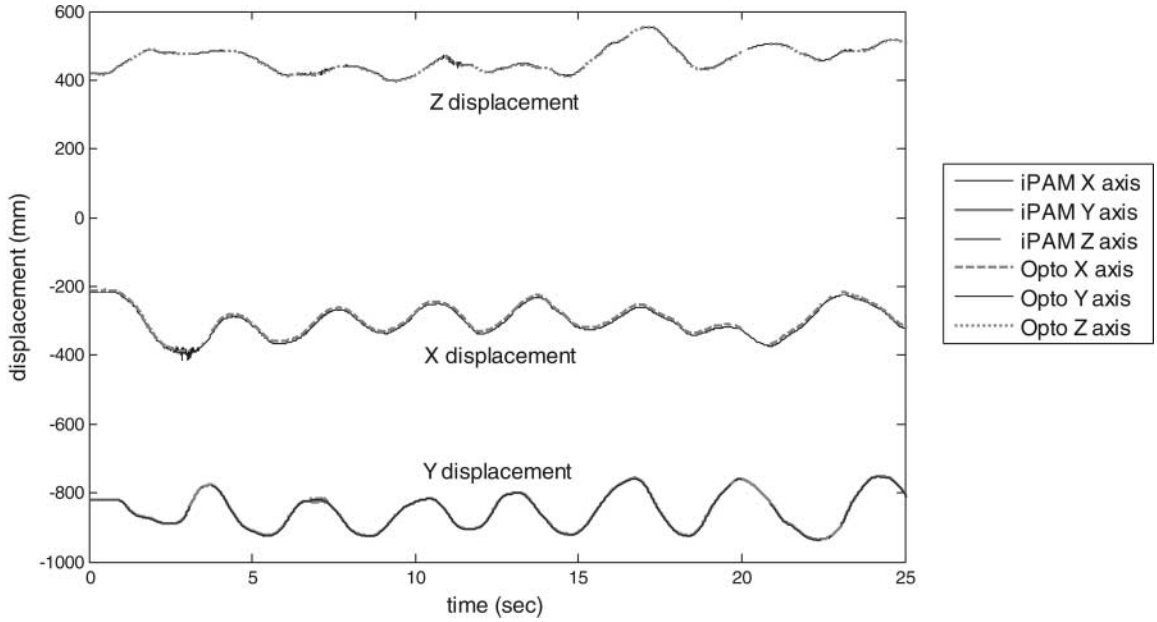

Fig. 7 Verification of iPAM measured *XYZ* Cartesian position of the end-effectors using Optotrak

4.1.2 Human joint-angle validation

The proposed low-level control method for iPAM utilizes independent impedance control around each human joint. In order for this to work effectively, iPAM must be capable of accurately determining the human joint angles as illustrated in Fig. 9.

A mechanical model of the human arm (Derryck) was attached to the iPAM system and swept through an arm trajectory utilizing the four rotational joints. Optotrak® was used to derive the relative angles of the arm's segments in order to measure the angles of the human joints.

Using knowledge of the starting shoulder position of 'Derryck' and the attachment points of the upper arm and forearm relative to the base joint of the upper-arm robot, it is possible to use the inverse kinematics of the human arm to on-line estimate the joint positions [**39**].The angular measurements of shoulder flexion/extension, shoulder adduction/abduction, shoulder internal/external rotation and elbow flexion/extension could be accurately estimated but translations at the shoulder were insufficiently accurate. An improved estimation technique is currently being worked on to address these limitations. Figs 10(a) to (c) show the measured and estimated joint angles for shoulder three shoulder rotational DoF while Fig. 10(d) shows the elbow flexion/extension. Results show iPAM is capable of estimating the human arm position within $\pm 5^{\circ}$. This is comparable to the errors typical of electrogoniometers when used to repeatedly measure joint angles on human limbs [**40**].

4.2 Comfort, safety and ease of use

Small-scale clinical trials were undertaken looking at the performance of the robot in a passive gravity assist mode. This mode allows the patient to undertake voluntary arm movements in the robot workspace while the robot is programmed only to lift its own weight and that of the orthoses. The aim was to determine whether the robot itself impeded voluntary movement through qualitative feedback from users.

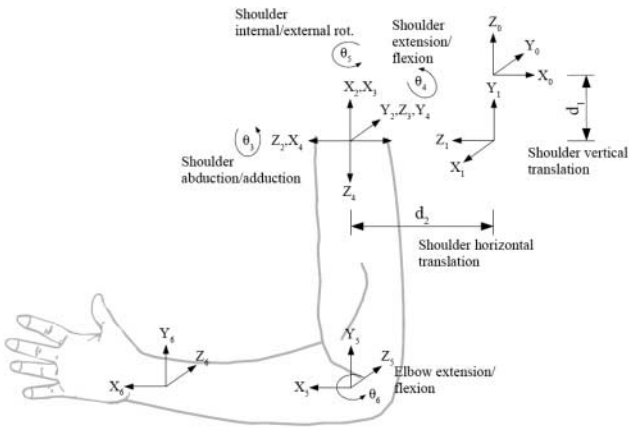

Fig. 9 Upper-limb kinematic model

Feedback was gathered through semi-structured questionnaires from six people with stroke and four therapists not involved in the project. Participants were given the option of filling in their questionnaire immediately after the session, or returning it by post. With one exception, every participant chose to fill in the questionnaire immediately. People with stroke can have communication difficulties, particularly with writing or with expressing themselves. Some patients asked the PT supervising the trials to write their answers onto the questionnaire. This introduces some validity issues, as patient feedback in these cases was not entirely confidential, which will be discussed further in section 5. Two physiotherapists and two occupational therapists (OT) tried the iPAM as if they were a patient, as well as using it from a therapists perspective. They were asked to fill in a patient questionnaire (coded to indicate that they were a therapist, not a patient), and also a separate questionnaire that presented questions specifically for therapists.

The questionnaires were a series of statements, each with five Likert type response options, on which participants could indicate whether they strongly agreed, agreed, were neutral, disagreed, or strongly disagreed. Space was also given for open-ended comments about each aspect of the design. The statements rated by the patient were as follows:

1. Comfort
   (a) being attached to the robot whilst it was not moving was comfortable;
   (b) being attached to the robot whilst it was moving was comfortable.
2. Ease of use
   (a) the robot was easy to attach to my upper arm;
   (b) the robot was easy to attach to my lower arm;
   (c) releasing my upper arm from the robot was easy;
   (d) releasing my lower arm from the robot was easy.
3. Safety
   (a) my arm felt secure while using the robot;
   (b) I felt safe while using the robot.

The therapists completed a similar questionnaire but with the comfort statements omitted, and the Ease of Use and Safety statements rephrased (e.g. 'I found it easy to attach the robot to the patient's upper arm'). In addition, supplementary questions on medical suitability were included:

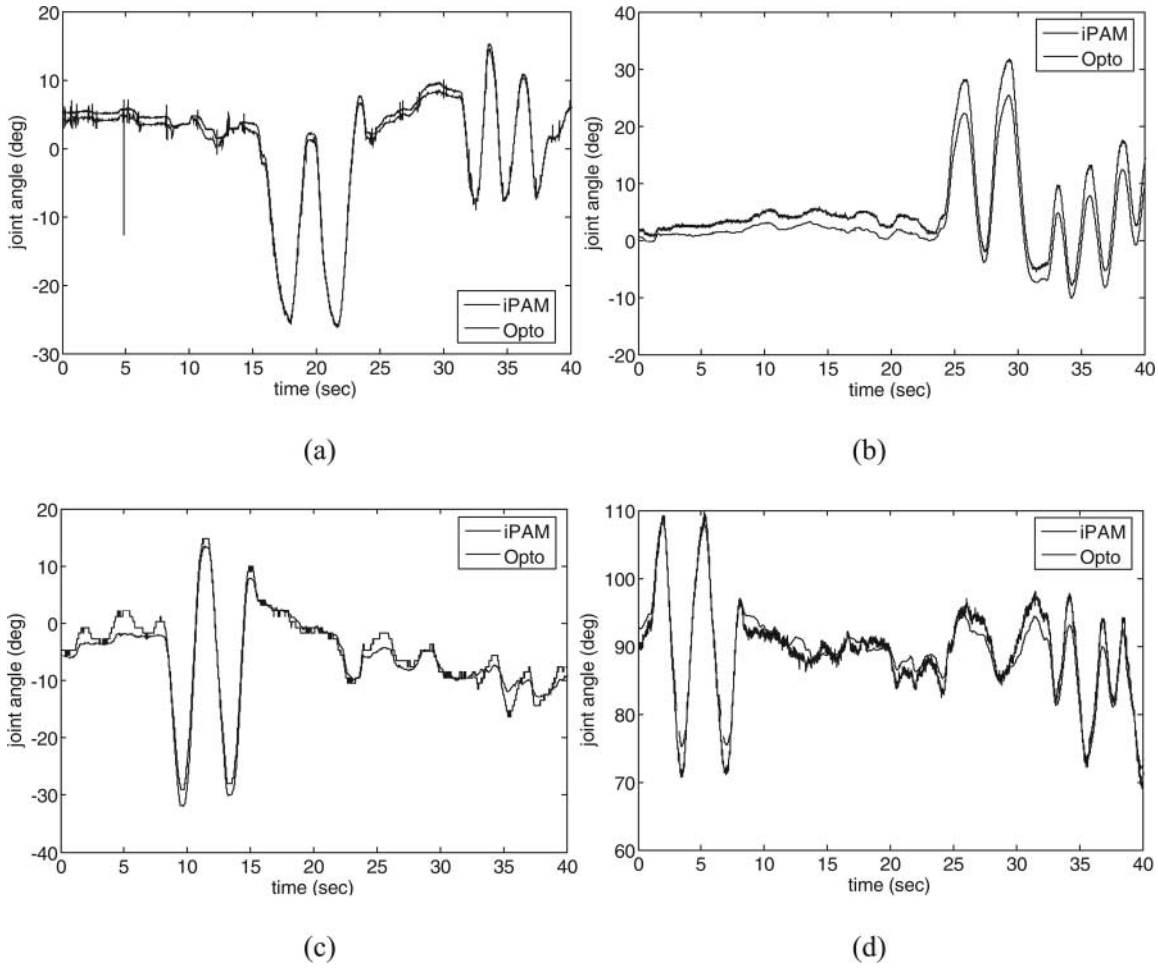

Fig. 10 Calibration of joints using Optotrak® and iPAM: (a) shoulder adduction abduction; (b) shoulder flexion/extension; (c) shoulder internal/external rotation and (d) elbow flexion/extension

(a) the robot enabled an excellent therapeutic range of movement;
(b) the robot provided a limited therapeutic range of movement;
(c) I consider the materials used for the robot attachments to be suitable for clinical use.

The response distributions were single-peaked, and with one exception, clustered across two adjacent points. Feedback obtained from the patients indicated that there was general agreement that the arm was comfortable while attached to the robot, and ease of attaching and removing the orthosis from the forearm. Two patients found that the upper arm orthosis was difficult and 'fiddly' to attach although removing it was not difficult. The therapists felt that the design of the orthosis was sufficiently easy to attach to the patients and remove it after a treatment session. The therapist also agreed that it 'looked safe' and provided a potentially therapeutic range of movement.

People with stroke often suffer a range of communication and cognitive difficulties. Engaging people with these impairments in design processes presents a challenge. Excluding their opinion can threaten the validity of user feedback within the design process. Arm impairment itself can physically restrict the patient's ability to communicate effectively. Many of the patients recruited for the evaluation were not able to write. In these instances the supervising physiotherapist acted as the scribe for the patient and wrote answers on the patient's behalf. This meant that questionnaire responses were no longer confidential, and patients may have been more inclined to give positive answers. Also, the supervising physiotherapist may have misunderstood the patient's feedback, or misinterpreted it, which may result in overly positive or negative feedback. People who have communication or other difficulties that may impact on their ability to participate in the design process should not be excluded, as it would create systematic bias by eliminating particular types of stroke patient from

the evaluation. Specific mechanisms are currently being developed to allow people with communication difficulties to be better engaged in the design process.

5 CONCLUSIONS AND FUTURE WORK

The paper describes the process used in developing and validating the mechanical configuration of a dual robotic system. Objective kinematic validation of the system has been conducted and user's subjective feedback presented. The intelligent Pneumatic Arm Movement (iPAM) system is shown capable of accurately tracking the movement of a patient's arm within a therapeutic workspace prescribed by physiotherapists. Using inverse kinematics of the human arm, it can determine the rotation of a patient's joints, providing a basis for coordinated human joint control. The involvement of the stroke patients and physiotherapists has been highlighted as well as difficulties encountered when involving end users with neurological conditions. User feedback demonstrates that the robot can provide a potentially therapeutic range of movement while also feeling safe and comfortable to the patient. This validation is due, in part, to the user-inclusive design process undertaken.

Future work will involve implementation of impedance control (lower level controller) in human joint space, rather than robot task-space as used on the single robot. This will allow the forces applied to be tailored to the patient's specific arm impairment, rather than providing a generic control at the end-effector of the robot. A higher-level controller will be developed incorporating a system for clinical data to be used by the lower level controller in implementing the exercise program. Computer visual display will be developed in addition to a modular 'real' workspace within which the patient can undertake appropriate exercises. Visual and auditory feedback of performance and error for the patients will be incorporated into the visual display.

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Queries

A E Jackson, R J Holt, P R Culmer, S G Makower, M C Levesley, R C Richardson, J A Cozens, M Mon Williams, and B B Bhakta

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