

# Development of a Dual Robotic System for Upper-Limb Stroke Rehabilitation

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**Abstract**— Stroke is a common condition resulting in 30,000 people per annum left with significant disability. In patients with severe arm paresis after stroke, functional recovery in the affected arm is poor. Inadequate intensity of treatment is cited as one factor accounting for the lack arm recovery found in some studies. Given that physical therapy resource is limited, strategies to enhance the physiotherapists' efforts are needed. One approach is to use robotic techniques to augment movement therapy.

Kinematic analysis of upper limb movement during a patient's physiotherapy session was used to determine the appropriate therapeutic workspace. An existing single robot arm is adapted to optimize its operating area to allow full movement in this desired workspace. The kinematic data is also used to look at the constraints involved in attaching two robot arms to the user's forearm and upper arm. An optimized design and configuration of the dual robot arms is proposed that allows appropriate control of the patient's arm throughout the desired workspace.

## I. INTRODUCTION

Stroke is a common condition (annual incidence 2 per 1000) and major cause of morbidity with 35% of patients left disabled [1]. Among those admitted with arm paresis, recovery in the arm is generally poor and has a major impact on self-care. A major component of arm rehabilitation after stroke is physical therapy. There is some evidence for a beneficial effect of physical therapy on recovery of the arm with a positive dose response relationship [2,3]. Even in rehabilitation services that purport to deliver an intensive program of physical therapy to patients with stroke, the amount of intervention may be inadequate because patients

spend a large proportion of time not engaged in "rehabilitation" activities [4]. Given that physical therapy is severely resource-limited, strategies to enhance the physiotherapist's (PT) efforts are needed. One approach is the use of robotic techniques to augment physical therapy.

Cozens [5] was the first to demonstrate electromyographically that responsive robotic assistance can be given during an active patient arm exercise. The efficacy of using robotics in stroke rehabilitation therapy has been investigated and proven by a number of researchers [6,7,8]. Several research groups are developing prototype robotic devices that have the potential to apply precise, quantifiable and repeatable movement therapy to stroke patients, however current prototypes tend to be complex and expensive [9,10,11]. The high power-to-weight ratio, low cost and direct drive capabilities of pneumatic actuators mean that the potential exists to make such devices simpler, and more affordable.

This paper focuses on the development of a dual robot system that allows co-coordinated physiotherapy exercises of the upper-limb to be undertaken. We have already used a single robot arm to aid in the rehabilitation process of stroke patients by providing task-based therapy similar to a PT. The robot is attached to the patients forearm via an orthosis. It assists them in making movements using an impedance control scheme [12]. The first prototype of the robot and the orthotic interface attaching it to the test subject, is shown in Fig. 1. A harness that is currently in development will limit the movement of the subject's torso.



Fig. 1. Current single physiotherapy robot

A dual robot system (REHAROB) has been developed for upper-limb rehabilitation using two industrial robots [13]. These allow full control of the patient's upper-limb while the

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patient lies supine. In this system one robot arm is floor mounted, the second is mounted overhead which makes the transportation and installation of the system very difficult. Also, the use of bulky industrial robots makes the cost per system very high.

In this paper a dual robot system is presented that is portable, relatively inexpensive and has the ability to assist a patient in undertaking arm movements similar to that a PT would undertake during treatment.

## II. SINGLE ROBOT REVIEW AND ITS LIMITATIONS

The 1st prototype robot, as shown in Fig. 1, uses pneumatic actuators to control the angles at three joints of a three degree of freedom robot arm. Joint-space PID controllers are used in conjunction with a task-space multi-degree of freedom impedance controller. This enables the robot to smoothly offer assistance to a patient when they are unable to follow trajectories independently. Further details of the impedance control are presented in [12]. Despite the effectiveness of the control system, the configuration of the existing robot system imposes limitations on its effectiveness to provide therapeutically useful physiotherapy exercises.

The first problem encountered is specific to the original robot design. The range of movement allowable by the existing robot is severely limited by the angles through which the joints can rotate. During a simulated physiotherapy session, a PT conducted a series of reach/retrieve movements on an able bodied subject while their arm was attached to the robot arm via the orthosis. In the course of these reach-retrieve movements, the robot arm frequently came into contact with the bump-stops situated at each joint. It is apparent that movement of the forearm, whilst undertaking routine physiotherapy exercises, is outside the allowable range of the single robot arm.

The second problem of a single robot design arises because a single point contact is used to interface with the upper-limb, located between the wrist and elbow. The orientation of the arm is therefore incompletely defined, with elbow and shoulder position under-constrained. When a PT undertakes normal upper-limb physiotherapy, two contact points are used: the forearm (close to the wrist) and the center of the upper arm. This gives the PT full control of the forearm, elbow and shoulder. Fig. 2 contrasts the desired elbow joint angle for a reach and retrieve movement with the actual movement achieved through single point contact. It was conducted using a dynamic simulation of a human arm assisted through a reach-retrieve maneuver by the 1st prototype robot [14]. It shows that, although the forearm follows a path leading to the same target during the exercise, the elbow joint is not constrained to follow the desired trajectory.

To solve this problem, a dual robot system is being developed that will mimic more accurately the type of

movement undertaken by the PT. This provides an additional point of contact on center of the upper arm. The orientation of forearm and upper arm can be fully controlled, while in addition providing support and exercise for the shoulder joint.

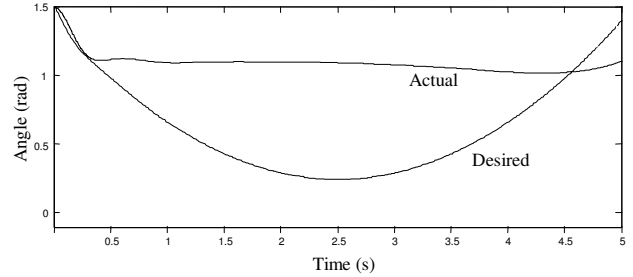


Fig. 2. Poor elbow joint coordination as a result of using a single point of contact to assist arm movement

## III. KINEMATIC ANALYSIS (ARM WORKSPACE)

### A. Motion Capture

The kinematic limitations of the first prototype robot, discussed in section II, highlight the need for an analysis of human arm movement during typical physiotherapy exercises.

An infra-red motion capture system was used to track the 3D position of a subject's arm during a set of simulated physiotherapy tasks. Markers were affixed to the shoulder, elbow and wrist to fully determine the orientation and position of the upper and lower arm. The test-subject was a healthy male member of the research team.

The workspace of the arm in physiotherapy tasks is usually a much reduced subset of the complete workspace achievable by an unimpaired person's arm. For example, movements such as reaching behind the patient's back are seldom performed. In this case, the tasks performed were typical of those regularly used in upper-limb physiotherapy; reach-retrieve, pick-and-place and hand-to-mouth movements. The motion capture data was processed to monitor the points at which a PT provides assistance, located at the mid-point of the upper-arm and wrist. Fig. 3 shows a side projection of the data with a simple representation of the arm at key points. The movement was predominantly in the anteroposterior (AP) and inferosuperior (IS) planes with limited displacement in the mediolateral (ML) plane.

### B. Kinematic Modelling

The experimental data discussed in the previous section gives a good indication of the movement range required for common physiotherapy tasks. However, it would be impractical and time-consuming to test every movement permutation possible. It is therefore useful to define a more generalized 3D workspace that encompasses a wide range of physiotherapy exercises, including those depicted in Fig. 3.

A workspace has been calculated using a 7 degree of

freedom kinematic arm model [15] in conjunction with a mathematical modeling package. By varying two parameters of the kinematic model and keeping the remaining set constant a surface (representing the position of the lower arm attachment point) is defined in 3D space. The full workspace can be constructed by combining these surfaces.

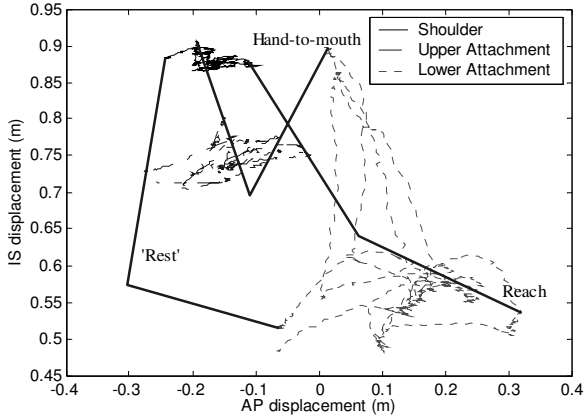


Fig. 3. Physiotherapy exercise trajectories

Kinematic parameters were chosen to describe the range of movements between the rest position shown and the full reach on either side of the body. This was refined by using the motion capture data illustrated in Fig.3. together with discussion with practicing physiotherapists. Firstly, the vertical movement range was restricted to shoulder and waist height. Secondly, movement lateral to the body was limited to  $\pm 0.2\text{m}$ . The resultant lower-arm workspace, and its orientation relative to the patient's body, is presented in Fig. 4. This fully encompasses the movements shown in Fig. 3. The desired workspace can be approximated to the black wire-frame cuboid shown.

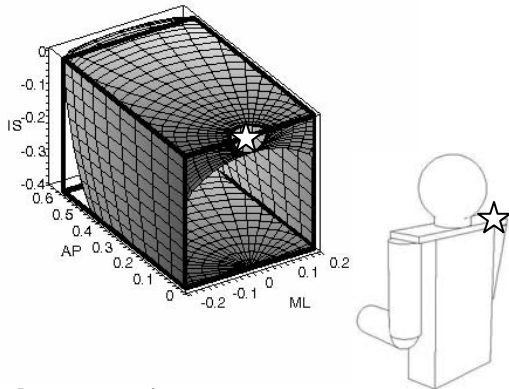


Fig. 4. Lower-arm workspace.  
The \* demonstrates the position of the shoulder in the workspace.

#### IV. LOWER ARM ROBOT OPTIMIZATION

As noted in Section II, the first prototype robot has a limited range of movement. To effectively analyze this limitation its kinematic model was used to calculate the workspace available. This is illustrated, in conjunction with

the desired workspace, in Fig 5. There is a large disparity between the two, particularly in vertical and lateral movement. It is therefore clear that the 1<sup>st</sup> prototype has an insufficient workspace to perform physiotherapy tasks, as defined in section III, and needs to be optimized.

The workspace visualization is useful not just in comparison and assessment, but also in optimization. In an iterative process, small changes were made to the kinematic parameters of the 1<sup>st</sup> prototype to ascertain their contribution to the workspace. From this process it was established that the largest limiting factors of the design were the narrow ranges of the joints.

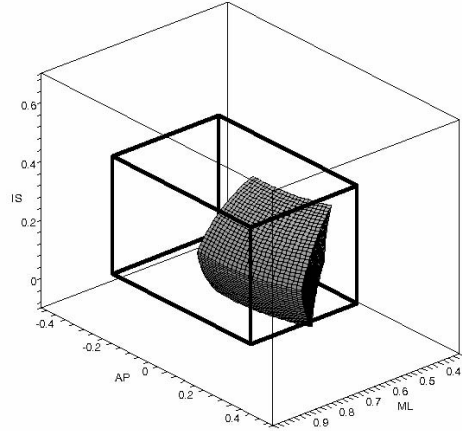


Fig. 5. Original robot workspace

A second iterative process was used to modify the kinematic parameters of the 1<sup>st</sup> prototype to achieve a workspace comparable to that desired. By slightly extending two links of the robot and increasing the joint ranges a much larger workspace can be achieved. The final result is presented in Fig 6. The robot covers the majority of the desired workspace and in some regions falls outside these bounds. These 'mismatched' regions are unavoidable due to the robots kinematic configuration of three revolute joints. Altering the configuration was deemed undesirable because of the ramifications on associated factors such as actuation and control.

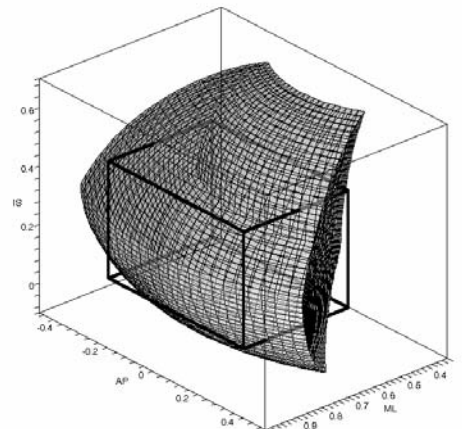


Fig. 6. Optimized robot workspace

As with any optimization process, the outcome is a compromise between the desired and attainable. Further extension of joint ranges was limited by the actuators which constitute a core part of the robot design. Similarly, the robot link lengths were constrained by the overall bulk of the robot and the actuators. Fig. 7. shows scale models of the 1<sup>st</sup> prototype and optimized robots. The position of the pneumatic actuators were altered to accommodate the increased joint ranges and link lengths. The increased workspace is evident.

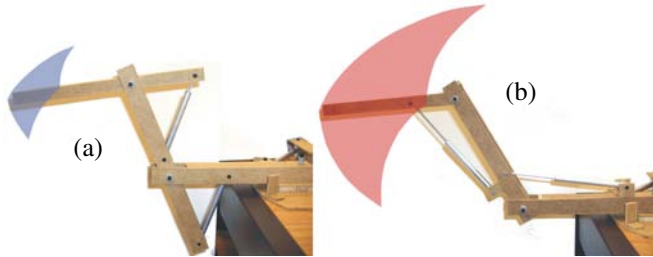


Fig. 7. 1:2.635 scale models of 1<sup>st</sup> prototype robot (a) and optimised configuration (b) in fully extended positions. A cross-section of their respective workspaces are superimposed.

## V. DUAL ROBOT SYSTEM

As outlined in section II, total control over the orientation of the patient's upper-limb demands two points of contact. When a PT applies force to the upper-arm during physiotherapy, it is applied approximately to the center of the upper-arm from behind. Fig. 3 shows that the range of movement of the mid-point of the upper arm is far smaller than that of the wrist. A desired upper-arm workspace has been defined using the same process as for the lower-arm. Analysis shows upper-arm workspace can be achieved using the optimised robot arm developed above. There are several advantages of using the same design for both systems:

- Production cost will be reduced as two identical robots will be manufactured.
- It can more easily accommodate both left and right-armed users as both robots will be capable of upper and lower arm movement.
- A reduced time to develop controllers for both arms as joint position controllers will be identical.

Fig. 8 shows a simulation of the dual robot system. Positioning the second robot behind the user mimics PT-patient interaction and allows the PT easy access to both robots and the patient's arm during operation.

## VI. DISCUSSION & FURTHER WORK

This paper has presented an analysis of the first prototype robot, revealing its present limitations. A series of kinematic optimizations are undertaken using prototype models and 3D visualization techniques. In addition, these methods were also valuable for communicating concepts within our multi-disciplinary research team. Lastly, a dual robot design,

emulating traditional physiotherapy, has been introduced.

The introduction of a second robot attached to the upper arm significantly increases the complexity of the system. Without careful consideration this could work to the detriment of patient safety. Ongoing work is currently exploring the suitability of different control schemes for the dual robot design. The current impedance control scheme used by the lower arm robot has been extended to independent impedance control for each robot. This will act as a benchmark, to be contrasted with a cooperative impedance control scheme currently being developed specifically for this application. An initial testing and development phase will use a dynamic model of the patient-robot system [14] before being extended to physical trials.

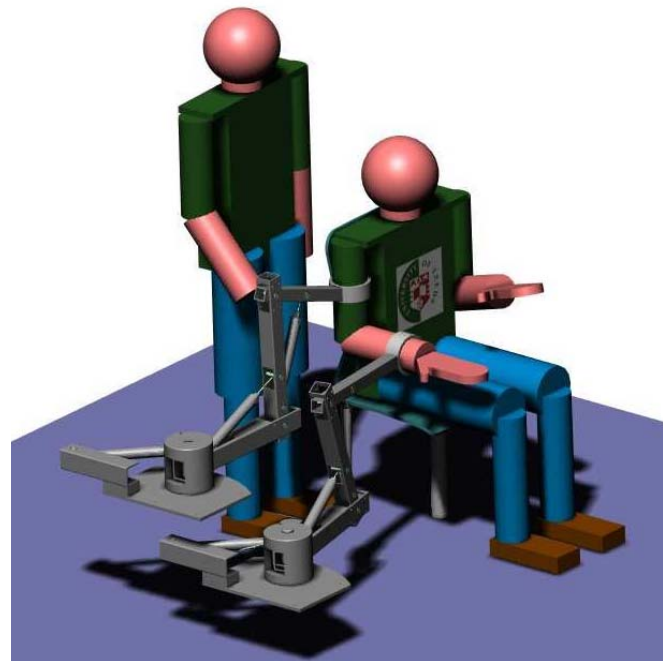


Fig. 8. Computer simulation of the dual robot configuration

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