Proceedings of the 2006 IEEE/RSJ
International Conference on Intelligent Robots and Systems
October 9 - 15, 2006, Beijing, China

A Cooperative Control Scheme for Robotic Rehabilitation of Arm Impairment after Stroke

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Abstract: Recovery of arm movement after stroke partly relates to quantity of functionally relevant practice. Physical therapies involve careful guidance of the paretic arm through therapeutic exercise to allow relearning of joint co-ordinations needed for functional arm movement. A robotic device that helps deliver more rehabilitation treatment would accelerate recovery of arm weakness. This paper describes the development of a cooperative controller for a robotic system (iPAM) that is being developed which will provide intelligent, interactive, safe movement treatment to help recovery of arm weakness after stroke.

I. Introduction

Research into robotic rehabilitation has seen significant growth in the past 20 years. In particular, there has been growing attention to robotic rehabilitation of the upper limb. This is not a trivial issue because of the range of complex movement the upper limb can achieve.

A number of robots have been previously developed to investigate and implement upper-limb rehabilitation. Early examples are MIT Manus [1] and Gentle/s [2]. In both cases a robot interacts with the patient through a single orthosis on the lower arm. Movement is defined in terms of the robot end-effector in robot task-space. The magnitude of assistance can be varied by impedance/admittance control schemes [3] that operate in robot task-space.

These rehabilitation robots and other similar systems have been successful in demonstrating the potential of using robotics in upper limb rehabilitation. A number of researchers [4,5,6] have shown that robot assisted exercise systems can produce significant improvement in a patient's functional outcome.

These findings are encouraging for the development of more advanced rehabilitation systems. The use of a single point of attachment on the patient's forearm causes some limitations. Those patients suffering from weakness or pain at the shoulder may be excluded because of insufficient support at the upper arm (e.g. mechanically moving the forearm alone may cause traction induced pain at the shoulder). Secondly, there is little provision to monitor or control the coordination and orientation of the patients arm.

Learning any motor skill involves achieving appropriate co-ordination between the movements at the various degrees of freedom (d.o.f.s) of the involved joints, thereby co-ordinating the velocity and position trajectories of the related body segments. For example, forward flexion of the shoulder and extension of the elbow are involved in advancing the hand when reaching [7]. During practice of a skill, patterns of co-ordination between d.o.f.s evolve according to the individual's learning behaviour. Conditions such as stroke may affect a patient's learning behaviour, through weakness, spasticity and impairment of perception or motor planning. If a rehabilitation robotic system is to facilitate patients' recovery it seems logical that it should take account of patients' learning behaviour, including the evolution of co-ordination over repeated exercise attempts

Recently a number of devices have been developed that seek to address some of these issues. The Pneu-WREX system comprises a 5 d.o.f. exoskeleton actuated by pneumatic cylinders [8]. The ARMin project features another exo-skelton based design [9]. Currently it features 4 wire driven d.o.f. and 2 passive d.o.f. Both systems have the ability to better support the patients arm throughout movements. In addition, the exoskeleton design provides the opportunity to control the arms orientation where the d.o.f. are active. Neither system use joint coordination as a foundation for their controller.

The intelligent Pneumatic Arm Movement (iPAM) robotic system under development through a collaborative venture between Universities of Leeds, Manchester and Aberdeen takes a different approach but with a similar goal of coordinated robotic intervention. Rather than an exoskeleton, iPAM features a dual-robotic design . Each robot has 3 d.o.f. and assists the patient via a specially designed orthosis, the first located on the lower arm and the second on the upper arm. The orientation of each orthosis is unconstrained, with each rotation axis passing through the arms centre. This configuration is analogous to the approach used by physical therapists when holding the patient's limb segments during conventional upper limb rehabilitation. The resultant 6 d.o.f control give the potential for control strategies that facilitate 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 limb orthosis also allows for full support of the shoulder complex during movement. Further information on the development of iPAM and it's goals are discussed in [10].

II. Controller Overview

In order to coordinate movement of the patient's arm the control scheme must necessarily be cooperative. The robots must act in unison, firstly with each other, and secondly with

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the patients arm. 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 [11], illustrated in Fig. 1.

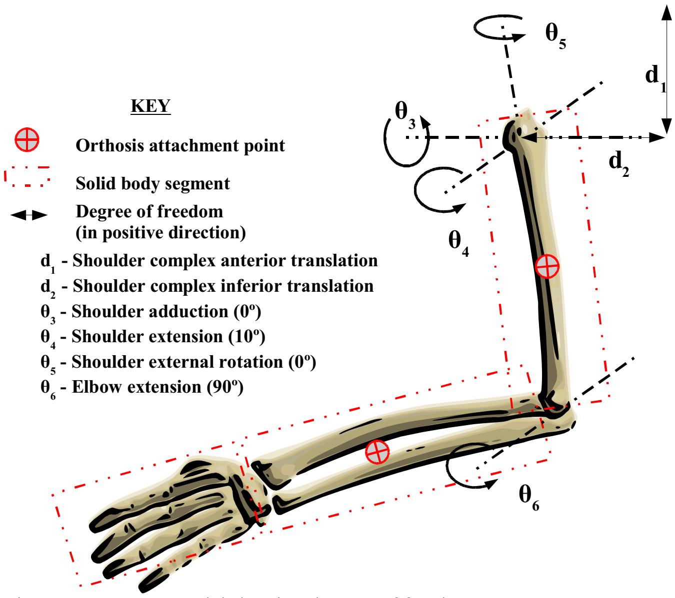

Fig. 1: Human arm model showing degrees of freedom, measurement conventions and solid body approximations. Flexion of the wrist is fixed at 0º.

Forward and inverse kinematics with respect to the orthoses have been developed for this kinematic model [12]. Consequently, a target trajectory can be defined in human arm space and transformed into each robots task space. A logical conclusion is to define robot assistance in the same human joint space. A Jacobian transpose method is used to resolve forces sensed at the two orthoses into the resultant forces and torques about each d.o.f. of the upper limb model. These elements have been combined to form an admittance control scheme that operates in human arm space. The admittance function modulates the input trajectory for each d.o.f. as a function of measured force/torque and takes the form:

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

where K and C are stiffness and damping terms respectively.

A schematic of the control scheme is shown in Fig. 2. This is in contrast to the existing schemes mentioned previously that define the level of assistance in relation to a single end point. For more detail on the control scheme see [12]

At the start of a robotic exercise session, the input trajectory to the control scheme is based on the kinematics of the patient’s limb. These are acquired as the limb is passively moved through the desired exercise manoeuvre by the therapist supervising the treatment. To take account of the patient’s learning behaviour as robot assisted exercise proceeds, we are developing a controller module which can revise the input trajectory (and associated assistance) after each movement attempt. The required revision will depend upon the changes in co-ordination exhibited over previous attempts and upon patient-specific clinical information supplied by the therapist, for example details of any perceptual impairment. These disparate data must be synthesised and interpreted using rules drawn from principles of motor learning, in so far as these are known to apply to stroke patients. For this purpose, we are developing a novel language: Synthesising and Interpreting Language for Clinical Kinesiology (SILCK.).

SILCK. components have been developed for characterising and tracking changes in co-ordination over repeated practice attempts. The approach is based on angle-angle cyclograms, which reveal co-ordination between pairs of d.o.f.s (e.g. elbow movement verses shoulder movement). The key features of these cyclograms are extracted using automatically-placed stationary points, which are interpreted with reference to task-specific expert templates. Changes in co-ordination may then be characterised as migration of stationary points over successive exercise attempts.

III. Experimental Setup

To investigate the behaviour of the cooperative control scheme a simulation was developed. The core elements of the admittance controller, shown shaded in Fig. 2, have been implemented in the Matlab mathematical modelling package. A dynamic model of the arm, discussed below, was implemented in the package and an inverse dynamics solver used to calculate the forces and torques at each d.o.f.. This provides a convenient way to explore the effects of altering the admittance controller parameters and biomechanical properties of the simulated arm. This allows rapid preliminary development of the cooperative controller system without the complications and risks associated with a physical testing environment.

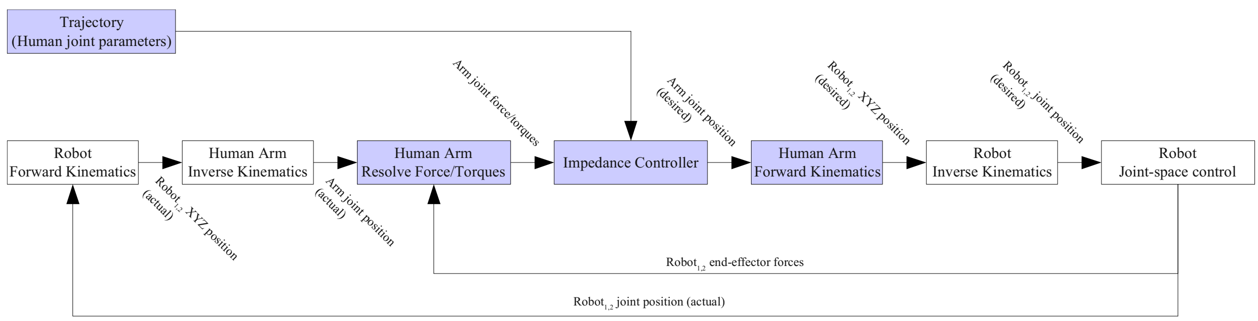

Fig. 2: A schematic of the cooperative human arm admittance controller

A. Human Arm Model

A full dynamic model of the human upper limb was required to test the controller. A solid body model was developed that provides a simple but powerful tool for investigating the behaviour and performance of the control scheme. The constituent parts of the model are presented below. Validation of the model in its entirety is the subject of current work. The solid body and kinematic approximations are illustrated in Fig. 1 and discussed in more detail in [12].

To obtain representative results the solid-body human arm model was configured to represent a 50th percentile healthy adult male. Anthropometric data [13] was used to define the length of each segment and its mass, centre of mass and inertial properties.

The model is currently passive, with no active force contribution to any of the degrees of freedom. The passive properties of each joint are modelled as second order systems, giving each joint a stiffness and damping characteristic.

Rotational degrees of freedom have been configured according to [14]. The study measured the stiffness and damping characteristics of the shoulder in abduction-adduction. In the absence of other data in the literature an assumption was made that these characteristics were also present during shoulder extension flexion and internal-external rotation.

The stiffness of the translational degrees of freedom at the shoulder were defined from [15]. No data was available in the literature for damping characteristics. Instead, the damping level was defined to give the same second order characteristics as for the rotational degrees of freedom.

Damping and stiffness characteristics for elbow extension-flexion were obtained for healthy subjects and those with varying degrees of spasticity [16]. Simulation of spasticity is desirable because it is a common feature of stroke. It is clinically defined as a velocity dependant resistance to passive movement and is well approximated by a spring-damper second order system [17].

B. Trajectory Definition

To test the impedance controller accurate trajectories of physiotherapy interventions are required. A 3D motion capture system was used to monitor several markers on a healthy volunteers arm whilst a physiotherapist applied a range of task-based interventions. The markers were located on standard bony extremities commonly used for motion capture. The cartesian coordinates of the monitored points were interpolated to find the simulated orthosis attachment points of the robot. The inverse kinematics for the human arm model was then applied to obtain the trajectory in terms of the human joint parameters shown in Fig. 2. A representative 'hand to mouth' movement is shown in Fig. 3.

IV. Results

A hand to mouth manoeuvre, shown in Fig. 3, was selected for the range of experiments. The movement is predominantly in the saggital plane. It features large ranges of shoulder and elbow extension-flexion that provides an ideal basis for testing the control scheme. The trajectory is defined in terms of each human joint parameter varying with time.

A healthy arm with normal tone, representative of a Modified Ashworth Score[1] (MAS) of 0, was simulated to investigate the effects of varying the assistance level applied about the elbow. The admittance controller was configured with a low level of damping sufficient to prevent an undesirable oscillatory response. Stiffness was then set to high and low values corresponding to high and low levels of assistance respectively. The shoulder's degrees of freedom were all configured to high levels of assistance. In all cases the high assistance was defined such that an arm with normal tone would closely follow the original movement. Low assistance was then defined as being one tenth this value. The level of assistance at each joint was fixed throughout the movement. Fig. 4 shows the results in comparison with the original movement.

The extension-flexion of the of the elbow is shown in the uppermost plot. Peak torques occur when the lower arm is parallel to the ground and the effect of gravity is greatest. It is evident that providing a high degree of assistance results in little deviation, in either position or torque, to the original movement. When the assistance is lowered there is a clear offset in extension-flexion, primarily because less torque is applied to oppose gravity. The general characteristic of the movement is retained, with no discernible phase shift or stretch. Above the plots is a saggital projection of the movement. It is clear that lowering the assistance does not affect the movement of the other degrees of freedom directly. The high level of assistance at these joints results in minimal changes to the original trajectory. Hence it is possible to isolate particular degrees of freedom for special attention in

[1]The Modified Asworth Scale provides a measure of spasticity – a velocity dependant resistance to movement – ranging from low (0) to high (4)

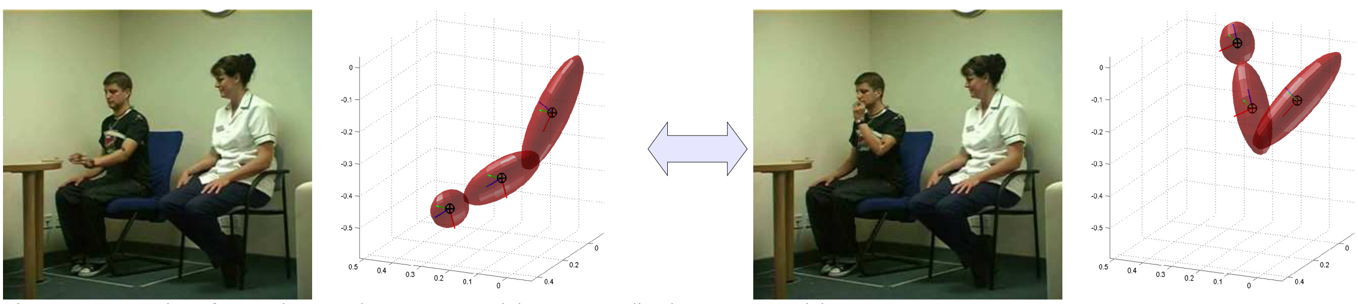

Fig. 3: Demonstration of a 'Hand to Mouth' movement and the corresponding human arm model

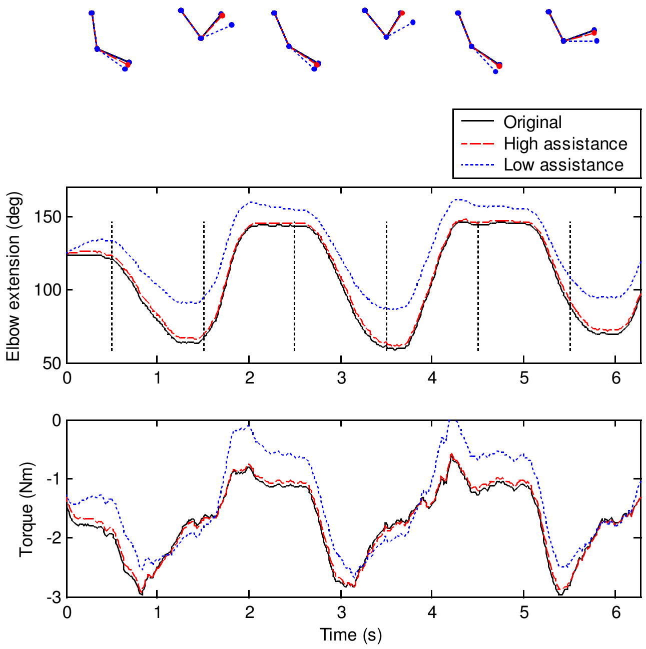

Fig. 4: Movement profiles for varying levels of assistance about the elbow joint for an arm with normal tone. Vertical dashed lines correspond to the time each sagital projection was plotted.

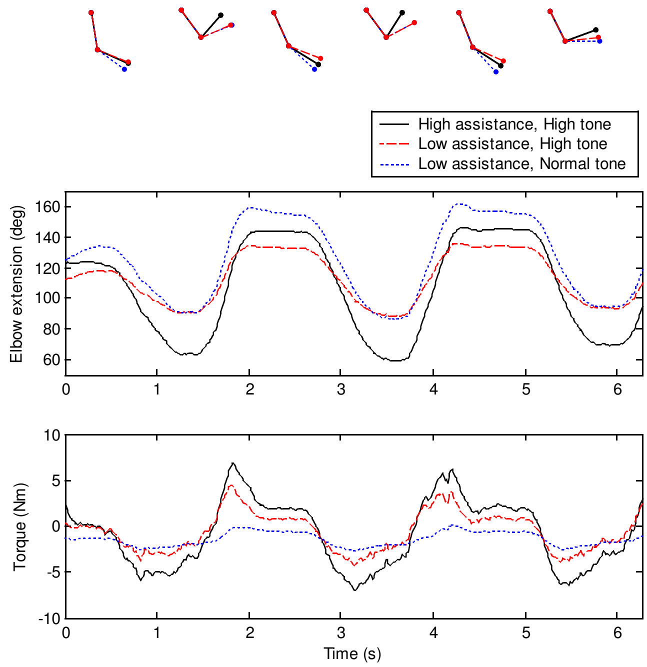

Fig. 5: Movement profiles for varying levels of arm tone. Vertical dashed lines correspond to the time each sagital projection was plotted.

directing the evolution of coordination during repeated practice.

Abnormal arm tone can significantly affect a persons ability to perform functional movements. To test the ramifications of arm tone on the admittance control scheme the characteristics of the elbow extension-flexion joint were varied. The admittance control scheme was set to provide a low level of assistance. The results are shown in Fig. 5.

Fig. 5 shows elbow behaviour with simulated high tone (MAS 4) and normal tone (MAS 0). As expected this highlights differences in movement characteristics. Simulated high tone results in a lower range of movement and requires significantly higher torques about the elbow to assist movement. Peak torques occur at high velocity. Importantly, although the general profile of movement is the same and the range differs there is no phase shift.

To investigate the impact of altering the assistance at more than one degree of freedom initially the arm was simulated to represent normal tone (MAS 0). Fig. 6 shows a cyclogram of shoulder extension-flexion plotted against elbow extension-flexion for a single cycle of movement. Different combinations of assistance about shoulder extension-flexion and elbow extension-flexion are displayed for comparison.

The loops in Fig. 6 characterise the coordination between shoulder and elbow extension-flexion. By decreasing the simulated shoulder assistance the cyclograms are moved to the left and compressed. Similarly, lowering the simulated elbow assistance shifts the cyclogram down and compresses it. This indicates that the overall range of movement is less and that it occurs about a displaced centrepoint. It is important to note that the general shape of the coordination loop is preserved in all cases.

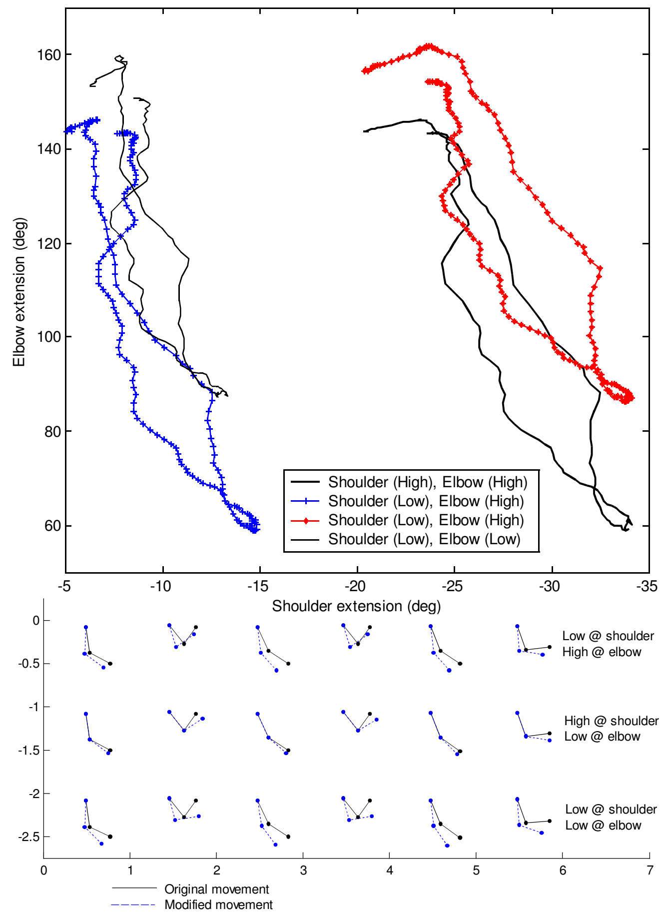

Fig. 6: Cyclograms of shoulder extension-flexion against elbow extension-flexion.

This derives from the coordination of the original movement being defined implicitly by the time-based trajectory of each joint.

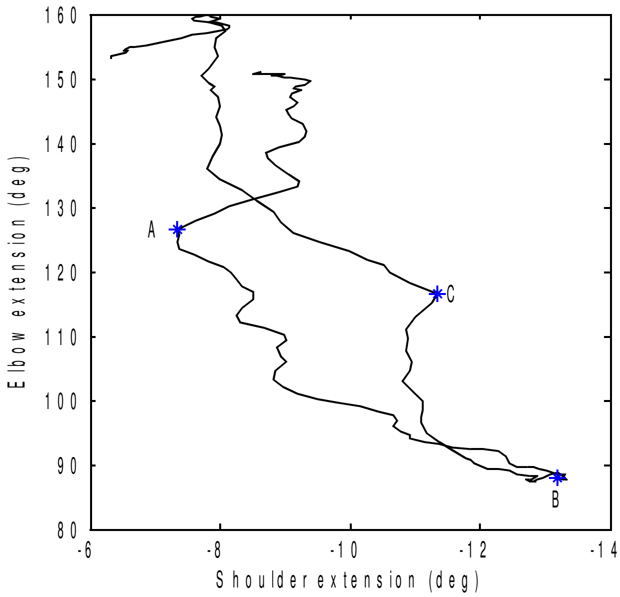

Fig. 7: A shoulder and elbow extension cyclogram showing stationary points for an arm with normal tone. Low assistance was simulated about for both shoulder and elbow extension.

Fig. 7 shows coordination analysis of the movement from Fig. 6 with low assistance about shoulder and elbow flexion. Stationary points identifying the key features of coordination between shoulder and elbow extension have been placed with the help of SILCK algorithms.

Stationary point B signifies the time at which the arm is fully raised. In the original movement this corresponds to the hand placed by the mouth. In this case with low assistance the hand is far lower. This is illustrated in the sagittal projections in Fig. 6 where stationary point B occurs at approximately 3.5s. It should be stressed that the stationary points identified in Fig. 7 are also present and comparable for each cyclogram in Fig. 6.

V. Discussion

It is clear that the cooperative admittance controller has the ability to target assistance to particular joints of the arm. This produces effects that are predictable in a passive limb model. Arm movement deficits after stroke occur due to a complex interaction of fluctuating neural and biomechanical factors. These result in abnormal, fluctuating patterns of muscle activation, hence more complex patterns of coordination are anticipated during clinical trials.

VI. Conclusions and Future Work

The robot and controller are now ready for clinical trials with stroke patients. Based on initial clinical experience, S.I.L.C.K. will be extended to incorporate rules whereby input trajectory is revised in the light of co-ordination and clinical data. These rules will cover issues such as variation of assistance during movement, and encouragement of exploratory learning behaviour. Since the effects of stroke on motor learning have been little studied, a putative initial set of rules will be based on principles of healthy motor learning. iPAM will provide an excellent experimental platform for testing the effectiveness of each putative rule in facilitating upper limb recovery. This will allow iterative refinement of the robot system.

VII. Acknowledgements

We would like to thank Jane Savage and Denise Ross for their assistance in defining the reference trajectories used in this paper.

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