Short Communications

Robotic Assistance of an Active Upper Limb Exercise in Neurologically Impaired Patients

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Abstract—**The principle of using robotic techniques to assist an active upper limb exercise is demonstrated in ten patients with weakness and spasticity. Using a servo motor to apply torque about the elbow, the mean range of active extension–flexion was increased in every patient. Sample kinematic and electromyographic (EMG) data are given.**

Index Terms—**Electromyography, hemiparesis, physical therapy, robotics.**

I. Introduction

ROBOTIC techniques offer the possibility of assisting simple active upper limb exercises for patients with neurological diseases such as stroke and multiple sclerosis. For this purpose, a robotic system must be responsive to the patient's performance: it should provide sufficient assistance to compensate for his/her impairments without transforming the active exercise into a passive manipulation.

Responsive assistance of a symmetrical bimanual exercise has been suggested for patients with unilateral impairment [1]. However, many patients have bilateral impairment and symmetrical bimanual exercises form only a small part of neuro-rehabilitation. For single limb exercises, enhanced recovery has been reported in stroke patients using a robot which guides the hand through desired trajectories [2]. This latter study is important for its demonstration of clinical benefit from robotic therapy. However, no kinetic or electromyographic (EMG) data were presented to illustrate the interactions of robot actuators with agonist and antagonist muscle groups, or the extent to which the patient engaged in active exercise. Since the robot did not directly assist component movements at the shoulder and elbow, it presumably had limited influence upon quality of movement over the whole limb. Like a physiotherapist seeking to promote desirable movement patterns, a robot should preferably act directly upon individual joints engaged in the exercise. This paper reports a pilot study in which the principle of robotically assisting an active single limb exercise is demonstrated using torque applied directly to an individual joint, with surface EMG to confirm active exercise and monitor the pattern of activity within the antagonist muscle pair.

II. Methods

A. Apparatus

The experimental apparatus is designed to study an abstract elbow extension–flexion exercise which makes no pretence to be a realistic therapeutic maneuver. As shown in Fig. 1, the patient sits with right or left shoulder forward flexed to 90°. The forearm is comfortably secured to a lever which can rotate in the horizontal plane about an axis aligned with the elbow. The proximal arm is immobilised in order that the lever may be moved only by elbow extension or flexion. Target lamps are positioned around the lever circumference; the lamps at locations corresponding to 10° and 80° elbow flexion are employed as extension and flexion targets toward which the lever is to be aimed. Angular movement of the lever is monitored by an electrogoniometer and an accelerometer. Concurrent EMG activity in biceps and triceps muscles in monitored via surface electrodes. A servo motor coupled to the lever applies assistive flexion or extension torque to the elbow. For safety, the motor is preset to a maximum torque of 2 Nm; this is less than the torque which is manually applied by a clinician during passive manipulation of a spastic upper limb.

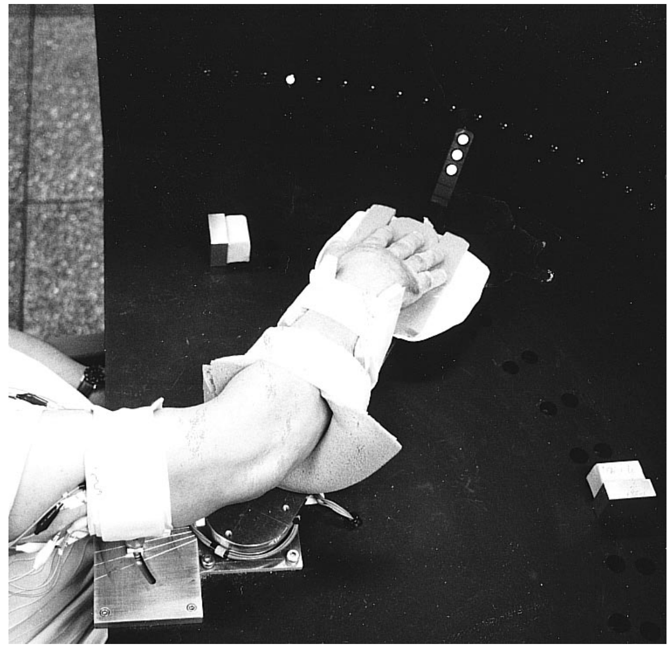

Fig. 1. The apparatus photographed from above, looking toward the patient's right side. The patient is moving the lever toward the flexion target lamp.

B. Control System

A computer-based control system monitors electrogoniometer/accelerometer signals and executes exercise and assistance algorithms. The exercise algorithm defines the required elbow movement by alternately illuminating the extension and flexion target lamps. The patient is requested to aim the lever toward each target; if the lever arrives at the target, the lamp is extinguished and the opposite target illuminated. Up to 5 s is allowed for each target. The sequence is repeated to a total of ten extension–flexion cycles per exercise.

The assistance algorithm (Fig. 2) specifies the torque to be applied by the servo motor. The algorithm uses criteria for which values (given in parentheses) had been established during unreported preliminary experiments with normal subjects and paretic patients. Provided the lever is not within a slowing zone (10° before the target), as-

Manuscript received February 27, 1997; revised January 20, 1998, October 7, 1998, and March 5, 1999. This work was done while the author was with the Rheumatology and Rehabilitation Research Unit, University of Leeds, U.K.

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Publisher Item Identifier S 1063-6528(99)04465-1.

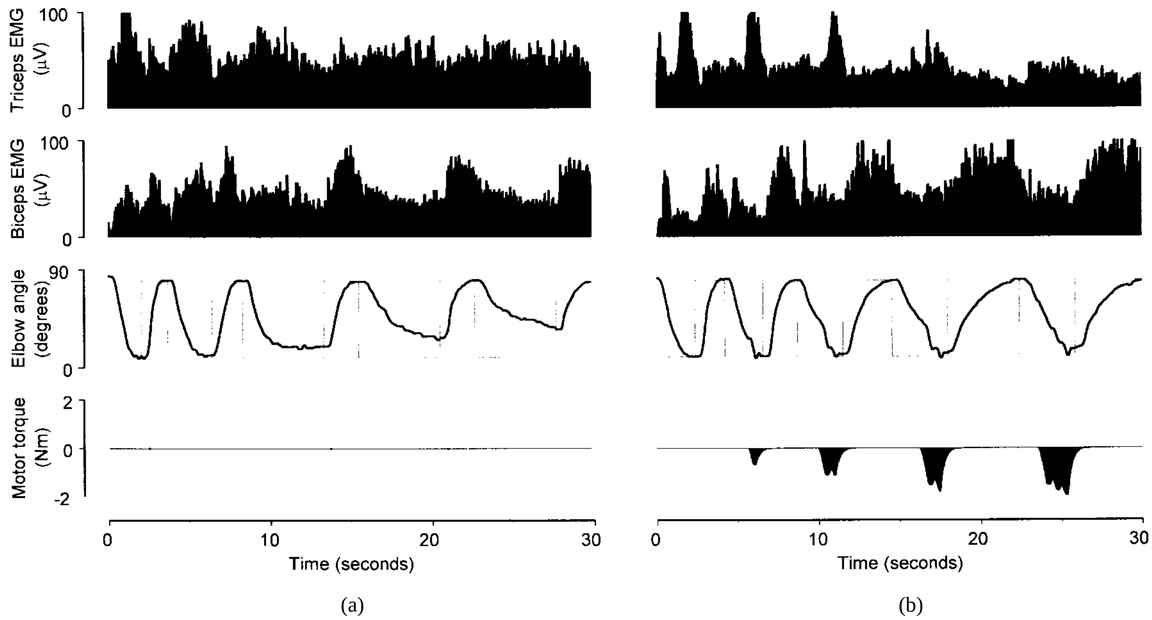

Fig. 3. (a) Sample records from an unassisted exercise and (b) an assisted exercise in a single patient. The first five cycles of each exercise are given. The motor torque plot shows assistance delivered as estimated from armature current; downgoing deflection corresponds to extension torque. The feint trace of the elbow angle plot denotes the angular position of the target lamp currently illuminated; the bold trace shows the actual angle of the elbow (as measured from the lever). Surface electromyographic (EMG) activity in the patient's biceps and triceps muscles is shown rectified and low pass filtered (-3 dB @ 20 Hz).

sistance is triggered by unwanted deceleration exceeding a threshold (50°/s/s); this ensures that torque is not applied before an initial active movement by the patient. Since patients with spastic weakness may make jerky movements which are not in need of assistance, unwanted deceleration only triggers assistance if it occurs in association with elbow movement below a minimum speed threshold (30°/s).

Once triggered, the assistance algorithm specifies a triangular torque pulse in the direction of the current target. Torque is gradually introduced using a 4-Nm/s ramp waveform to avoid an unwanted antagonist reflex response. Once it reaches 2 Nm or elbow movement exceeds a maximum assisted speed (60°/s), torque is withdrawn using a 2 Nm/s ramp. This avoids transforming the exercise into a passive manipulation. Further assistance may be triggered by recurrence of the unwanted deceleration/minimum speed criteria, until the lever enters the slowing zone before the target, or the 5 s period has elapsed.

C. Patients

Ten stroke or multiple sclerosis patients aged 47–69 years were recruited with informed consent. Each exhibited weakness of an upper limb, such that he/she could move the lever a little but was unable to complete an unassisted ten-cycle exercise with full movement between target lamps on every cycle. Some patients also exhibited spasticity. Exclusion criteria were elbow contracture and shoulder pathology preventing comfortable limb positioning.

D. Experimental Procedure

The experimental procedure was approved by the local ethical committee. It comprised a series of exercises, each with ten extension–flexion cycles. During some exercises, the assistance algorithm operated as described above ("*assisted exercises*"); during other exercises, it was switched off ("*unassisted exercises*").

A practice period was provided in which unassisted and assisted exercises were interleaved in an irregular sequence without forewarning. There followed two exercises during which target angle, EMG activity, elbow movement and motor torque were recorded. Still without forewarning, the first of this pair of recorded exercises was invariably unassisted and the second assisted. The assisted exercise was invariably recorded last in order that fatigue or spasticity from previous effort would, if anything, diminish any apparent benefit of assistance.

For each patient, records of the final unassisted and assisted exercises were analyzed as follows. The mean range of elbow movement during an exercise was derived by averaging the angular ranges recorded for each of the ten cycles. The total assistance given during an exercise was estimated by rectifying and integrating the motor torque record.

III. Results

All ten patients could undertake the unassisted exercise, and be given assistance, without discomfort. Fig. 3(a) shows the first half of the unassisted exercise recorded in a representative multiple sclerosis patient. After the initial two cycles were completed with considerable effort, biceps spasticity (exacerbated by effort) offered increasing resistance to extension over the third to fifth cycles. Fig. 3(b) shows the first half of the assisted exercise recorded in the same patient. After the initial cycle, the motor provided increasing assistance to elbow extension; the assistance enabled the patient to achieve a full extension–flexion range in all ten cycles. EMG records confirm active exercise: reciprocal activation of the antagonist muscle pair is seen, although some unwanted biceps activity persists in the extension phases.

Fig. 4 shows that assistance increased the mean range of active elbow movement in every patient. This increase was statistically significant on two-tailed unpaired t test ($p < 0.01$) for all patients except the two individuals represented by open symbols ($\delta\nabla$). The responsive nature of the assistance is shown in Fig. 5: this employs mean range of elbow movement in the unassisted exercise as an index of exercise capacity. Against this index for each patient is plotted the total assistance given in the subsequent assisted exercise. It is evident that greater assistance tended to be given to patients with more limited exercise capacity.

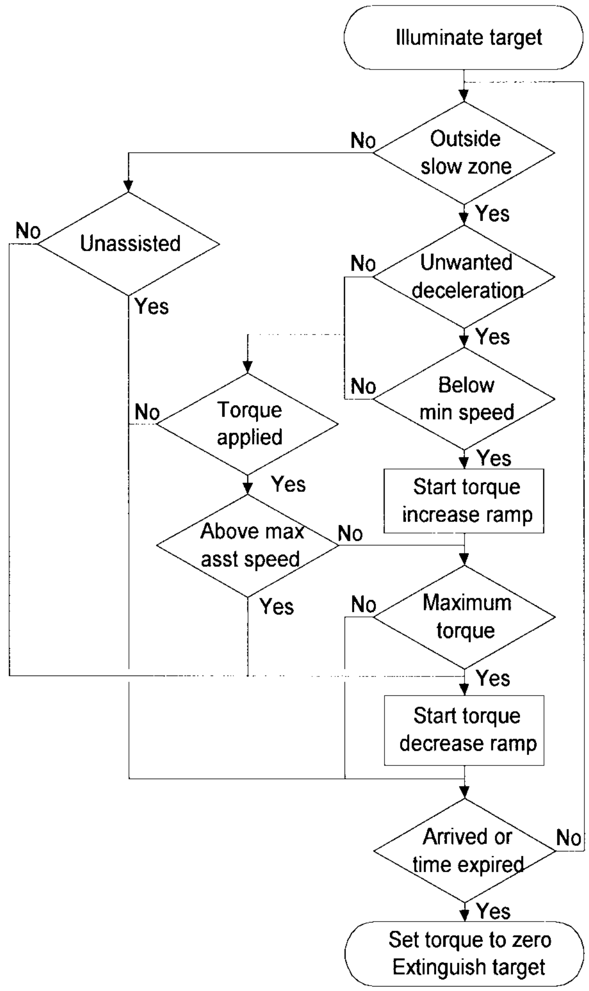

Fig. 2. The assistance algorithm for a single movement phase (extension or flexion). This would be repeated 20 times in a standard exercise of ten extension–flexion cycles.

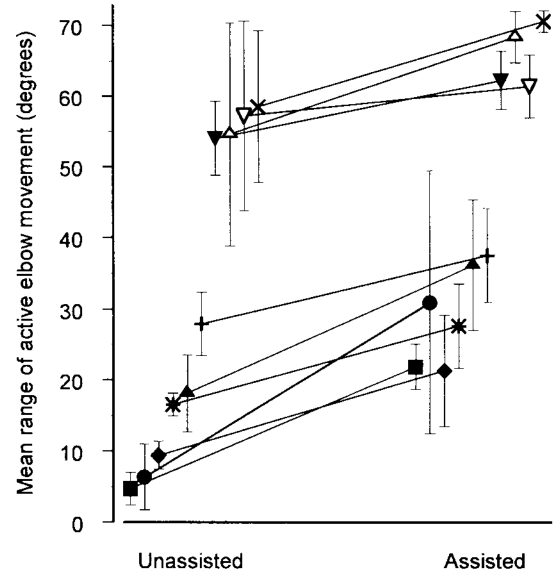

Fig. 4. The effect of assistance in ten patients: each pair of datapoints describes the final unassisted and assisted exercises recorded in an individual patient. Datapoints denote the mean angular range of active elbow movement ($\pm$ standard deviation) over all ten extension–flexion cycles of the exercise in question. Patients represented by datapoints ⧫, ■, •, and $\times$ had a diagnosis of multiple sclerosis; the remaining were stroke patients.

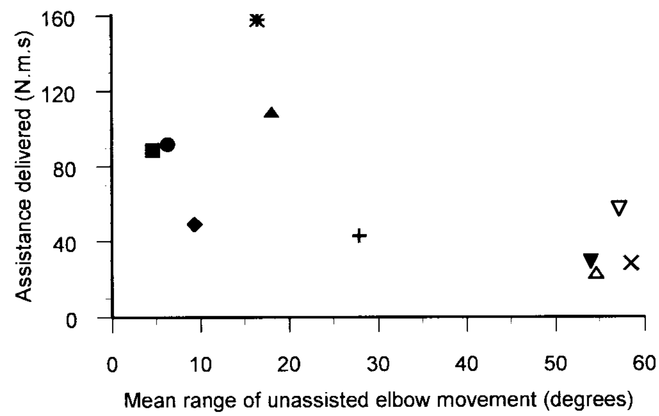

Fig. 5. For each patient in Fig. 4, the total assistance delivered by the motor during the assisted exercise is plotted against the mean range of active elbow movement in the preceding unassisted exercise.

IV. Conclusion

The principle has been demonstrated of assisting an active single limb exercise using a responsive robotic technique which applies torque directly to an individual joint. A robot must now be developed for realistic therapeutic exercises, at least involving three degrees of freedom at the shoulder and two degrees of freedom at the elbow. Since impairments such as spasticity differ widely between patients and may even vary during the course of an exercise session, an adaptive control system would be appropriate.

Acknowledgment

The author is indebted to Dr. B. B. Seedhom for encouragement and criticism, to Dr. B. Bhakta, M. Pullen, and B. Witham for help in constructing the apparatus, and to Dr. A. R. Plummer and M. Austin for advice on flow chart design. The cooperation of the patients, approved by Prof. M. A. Chamberlain and Dr. V. Neumann, was greatly appreciated.

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