Force Feedback Joystick Therapy for Children with Cerebral Palsy

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\section{1 Introduction}

Cerebral palsy (CP) is the commonest cause of severe physical disability in childhood, affecting 1 in 400 children. It is a heterogeneous group of motor disorders which affect posture and movement. It arises from non-progressive brain injury occurring before, at the time of, or immediately after birth. The distinguishing effect of this injury is abnormal motor development resulting in muscle weakness, spasticity, poor coordination and difficulty with balance. This may be manifest as delay in achieving motor milestones as the child develops resulting in difficulty with sitting, walking, running and arm movement. Although the brain injury is non-progressive, the impact of this on the developing brain results in clinical features that may change as the child grows (for example, spasticity which may not be very apparent at the time of diagnosis becomes very troublesome as the child matures). Owing to the varied types and extent of brain injury these children may also have other problems such as epilepsy, vision or hearing impairment, learning disability.

Difficulties in movement and posture (Becher,1988) arise from (a) disturbances in muscle activity which can be divided into negative effects (loss of muscle power
and coordination), positive effects (involuntary muscle contractions such as co-contractions of opposing muscles), and other effects (e.g. abnormal reactions to skin stimulation); (b) disturbances in muscle stiffness: decreased flexibility of muscles because of changed mechanical properties and (c) disturbances in muscle length with shortening. Rarer types of cerebral palsy cause different types of disordered movement such as athetosis or ataxia.

Physical therapies (including exercise, orthotics, and 24 hour posture management), pharmacological management of spasticity and surgical correction of deformity are important components of conventional treatment. In the last ten years, there have been several research projects into new CP therapies. Berg-Emons (1996) states that aerobic sessions can result in patients accomplishing significant gains in aerobic power and muscle strength as well as reduction of spasticity. Thorpe et al. (2001) developed a ten-week program in which nine spastic diplegic CP patients performed aquatic exercises. They improved strength, balance, functional mobility and self-perception. Lathan et al. (2001) describes a robot for disabled children, which operates by the child’s voice and body movements. The robot, which looks like a furry stuffed animal, mimics the actions of the child. The robot can function in a classroom, so the child can attend classes through the robotic interface. Rewards presented by the device such as a funny robot-dance when the child attempts the tasks they are supposed to learn provides additional incentive for the child.

Although the focus of intervention is on posture and mobility, the impact of CP on arm movement can cause significant activity limitation. Arm movements may be less smooth and appear uncoordinated with the presence of involuntary movement. Children whose arm does not move properly are naturally reluctant to use it. This may result from a combination of weakness, spasticity, loss of selective muscle activation and presence of abnormal movement (e.g. those associated with effort).

Conventional intervention is directed at encouraging the child to use the arm in day to day activities. With practice, children can make improvements in their eye-hand coordination (Miller et al., 1998). However despite conventional treatments, some children do not recover functional arm use.

An important determinant of the extent of improvement in arm function is whether the child is able to undertake appropriate functionally useful exercises at sufficient intensity. Unfortunately exercises that are prescribed are often uninteresting for children to do. Therefore it becomes difficult to maintain the child’s enthusiasm for doing the exercises even when the child may understand the need for them. The need for the child to undertake appropriate exercises is also crucial if spasticity treatments such as botulinum toxin are being considered. The ability to reach and retrieve objects is a crucial component of arm function.

Recently there have been a few reports of using emerging technologies to provide mechanised assistance to deliver arm exercise treatment. Reinkensmeyer et al. (2002, 2003) implemented a force feedback joystick for patient data collection and passive exercises to investigate speed, co-ordination, and strength. Nair et al. (2003) developed a system to use a commercial force feedback steering wheel to assess patient’s performance for a racing car game. All these studies show the
potential for improving physical abilities with well-designed exercise program in combination with appropriate technology.

The focus of this project is this area of arm movement. A mechanised system that allows the child to undertake relevant exercises which are fun to do may be a useful adjunct to the conventional treatments. The commercially available arm exercise machines are limited by the type of exercises that can be performed using them. In particular they are of limited use as the amount of movement afforded by the use of the available device falls far short of the arm excursions that are required during day to day arm use. We have developed a device that may be useful in assisting appropriate upper-limb practise in children with CP. The practise method consists of computer gaming exercises and a modified force feedback joystick. This pilot study investigates the feasibility of this approach. All parents and children were given verbal and written information about this study. Written consent was obtained. The hospital ethics committee granted ethical approval for this project.

2 Force Feedback Joystick

Force feedback joysticks are relatively new for home computer gaming applications and have only been mass produced in the last 10 years. Force feedback is applied during games to increase the realism of the game by applying forces that are similar to those that would be felt if actually performing the task. Through mass commercial manufacture, the cost of these devices is kept to a minimum (£50-£100). Moreover, development of the universal serial bus (USB) interface allows connection to any modern PC without the need to add additional hardware.

The approaches taken by Reinkensmeyer et al. (2001, 2002, 2003) and Nair et al. (2003) do not implement the full potential of the devices for movement therapy thorough the application of assistive controllers. Furthermore, the modifications of the devices do little to make their limited movement range more appropriate for movement therapy.

Here a force feedback joystick has been modified with an extended shaft to alter its movement from a two-angle wrist rotation to a reach/retrieve movement in two axes for children with cerebral palsy (Figure 1). Interchangeable shafts enable the movement range to be quickly altered for different children. The downside of the increased shaft length is that the maximum force that can be applied to the hand is reduced. The joystick is mounted on a platform that allows full control over its position and height in relation to the child. This adjustment is necessary so that exercises can be performed correctly on children with cerebral palsy and ages ranging from 6 – 13 years old.

Children are likely to benefit from this approach the greatest as they have smaller movement range than adults and require less force to assist their motions. Furthermore, children are more inclined to work with computers and likely to gain more enjoyment from their use. The joystick is only one part of the exercise system. Computer game software has been developed which enables the children
to play games whilst the joystick provides active assistance forces, thus facilitating movement therapy. The software is described in section 3.

![Figure 1. Force feedback joystick with extended shaft for greater reach/retrieve range](image1.jpg)

### 3 Therapy Software

Computer software has been developed to control the joystick and provide motivational entertainment to the children during exercises. The joystick connects to the computer by a Universal Serial Bus (USB) port and communicates through Windows API DirectX software. The software was implemented using Borland Delphi 5. The joystick driver software enables several effects to be activated on the joystick such as vibration and force output while measuring the joystick angular rotation in two axes.

The computer exercises have been developed that require a cartoon character to be moved across a computer screen following a predefined trajectory, with the trajectory varying by an adjustable degree of randomness. Two versions of the software were developed; a football game (Figure 2a) and a monkey game in which the monkey has to collect bananas and place them in a basket (Figure 2b). The games have identical principles and the only difference is with the characters and background pictures to keep the children entertained.

The modified joystick allows hand movement in the X plane (across the body) and Y plane (away from and towards the body), see figure 1. Rotation of the joystick shaft also results in slight uncontrollable movement in the Z axis. The maximum Z movement is approximately 10% of the X and Y movement and therefore considered not to be significant. The X and Y coordinates are scaled and mapped to the position of a computer character with horizontal (X) and vertical (Y) computer screen coordinates (the extremities of joystick motion are the edges of the screen).

It is important to make a distinction between absolute coordinate mappings of hand position, as implemented here, and the velocity based mapping used in the majority of computer games. Velocity based mapping takes the angle of the joystick and converts it into a change in position of a computer screen character. Therefore the fastest way to move between two points is to move the joystick to its
full angle (greatest velocity) and then to zero position, encouraging un-coordinated movement between extremes of motion. In the absolute system, the fastest way to move between points is to move the hand as quickly as possible to a precise position in space, thus encouraging coordinated movements. Without force feedback this system can be used as a measurement tool (for performance characterisation) and exercise.

Figure 2. (a) Screenshot of the monkey game, (b) screen shot of the football game

Controlled forces can be applied to the hand, which assist the child’s voluntary arm movement. The force output from the joystick can be updated at regular intervals, and the angular position measured (in this case every 50ms) allowing implementation of impedance control (Hogan, 1985). Impedance control allows the relationship between force and position to be set to a mass, spring and damper system. In this initial study, the relationship between force and position is a pure stiffness. Note the joystick force control is based upon open-loop model based control, and as such is likely to have small errors. To improve the control of applied forces additional force sensors would need to be attached to the device, however the open-loop force controller is sufficient here. Figure 3 shows the controller block diagram. The controller aim is to cause the error between the child’s X & Y hand coordinates and desired coordinates to be zero. The stiffness (K) controls the amount of force applied to the hand. A more able child would exercise with a small value of K therefore little force will be applied to assist motion.

Larger values of K provide greater assistance through more force output for the same position error. Ideally K would be a linear constant to provide a gradually decreasing force output as the position error decreases (Figure 4a). However, due to limitations in the maximum force output this would result in little assistance being applied when close to the target. Furthermore, it is important to implement a ‘dead zone’, for small position errors, in which no force is applied to prevent overshooting the position. A non-linear K function was implemented with a dead zone and region where the force applied is constant at the maximum (Figure 4b). The dead zone, saturation level and stiffness are all preset by a therapist before
commencement of the exercise. The force feedback joystick and software was tested on three children with cerebral palsy to assess its potential.

![Control block diagram of joystick force assistance](image)

**Figure 3** Control block diagram of joystick force assistance

![Control block diagram of joystick force assistance](image)

**Figure 4** (a) Linear stiffness (b) non-linear stiffness with deadzone and force saturation

### 4 Experimental Tests

The force feedback system was tested on three children with CP: a boy of seven years old, a girl of seven years and a girl of nine years. All these children had movement difficulties with their right arm. The girl of seven used a short extension of 0.30m in length resulting in a total reach of 0.21m in horizontal and vertical directions, and the others used a long one of 0.42m resulting in a total reach of 0.28m in both directions.

The test sequence of the first two children involved playing five games of two minutes duration twice. “Assistance force” for each set of games was applied in the following order: a) no force, b) low K, c) high K, d) low K, e) no force. This sequence was used to test the influence of the force feedback, reducing the influence of the expected improvement due to becoming more familiar with the game. If child improvement were purely through familiarity with the game, then the children’s performance during tests d & e would continue to improve.

The children had three minutes rest in between the trials to lessen the effect of muscle fatigue, and half an hour between each set of five games. The test sequence of the third child was: a) no force, b) no force, c) low force, d) low force, e) high
force. In this way, we hoped to identify any other unconsidered factors that might be influencing the child’s performance.

During the exercise joystick positions, control signals, targets objects positions, velocity, and the amount of force feedback were recorded every 50ms. An electrogoniometer measured the elbow angle to assess the arm position during the exercises (see Figure 5). This additional measurement along with arm lengths and hand position allows the approximation of the whole arm position.

![Goniometer and joystick setup](image)

**Figure 5.** A test subject with her arm attached to a Goniometer, holding the joystick

Example data is shown in Figure 6 when testing the same subject with and without force feedback. The absolute error is vector magnitude of the X and Y error coordinates. On the vertical axes the symbols indicate the time when a new target has been allocated; the ‘⊗’ symbol is for the graph without force feedback and the ‘Ο’ symbol is for the graph with force feedback. A new target is specified when the previous has been reached, and all the target steps form a movement trajectory. The absolute error shows the dynamic performance of the hand moving to reach the desired target. The graph also shows the actual X & Y hand positions during the exercise.

The 10 seconds of exercise show the hand to move smoothly between over an approximately 0.2m range in X and Y. It is difficult to assess the performance with and without force over the ten-second period. Indeed, in this particular time sample more targets are reached without force feedback (as indicated by the symbols on the horizontal axes). The score during the game is the scaled and summated vector magnitude between targets during 2-minute game sessions, which is the total distance travelled if the exercise were performed perfectly. Therefore, the score can be used as an approximate quantitative assessment of the benefits of force feedback.

The relation between the force level and the end-scores of the test subjects are shown in Figure 7. The first game of each test session of five trials was used as an introduction game with different settings, so the child was familiar with its operation. The x-axis is the different values of force assistance used during the game, and the y-axis is the respective score. The low force setting appears twice due to the ‘peak’ sequence used to assess the subjects (no force, low force, high force, low force, no force).
Figure 6. Data from a test subject with cerebral palsy with and without force assistance.

Figure 7. A comparison between force feedback settings and resulting end-scores.
The children obtain their best results when the force feedback level is highest, as apparent in the average of all the children's scores. An exception is trial 3.2, but that result was caused by concentration problems of the test subject. Fatigue effects did not seem to have a large influence on the performance of the children. They became tired towards the end of each two-minute trial, but indicated that the fatigue had ended during the 2-minute break between exercises. These results indicate that the force output from the joystick is helping to improve the child's performance by applying assistive forces. Further tests are required to assess whether the exercising with the system has the capability of improving the child's ability to move their arm when not playing the game.

5 Dynamic Arm Exercise Playback

It is important to be able to assess arm movements after the exercise has been completed. Joystick positions are measured by the joystick and the goniometer measures elbow flexion, however the raw data is difficult to visualise. A post-exercise human arm simulator has been developed with the capability of replaying movements in 3D for post-exercise visualisation. The simulation has been developed in OpenGL assuming the shoulder movement to be limited. Additional sensors on the shoulder would enable exact reconstruction of movement. Figure 8 shows a screen shot of the arm motion visualisation.

![Figure 8. Screenshot of OpenGL arm simulation](image)

6 Conclusion

All the children experienced the force feedback assistance as comfortable. Force feedback has a positive influence on children suffering from Cerebral Palsy through improving their ability to perform reach/retrieve exercises when holding the joystick. The more force is applied, the better the children perform. Effects of fatigue can be the reason that the scores of test subjects 1 and 2 decrease after three trials, but the tests of subject 3 show that in the ten minutes the children play the game, fatigue has no influence on the score.
On some trials the children were observed to play the game without flexing / extending their elbow (using trunk flexion and extension to control the joystick). This is a limitation that needs to be addressed, as one of the main aims of the system is to encourage children to practise reach / retrieve movements.

Further research will focus on (a) comprehensive evaluation of the joystick movement range offered by each of the video games and to adjust the games so that the envelope of movement practised is the desired one, and (b) the influence of force feedback on the child’s unassisted movements.

The device has shown potential to greatly benefit children in a home environment.

7 References

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