Upper Limb Robot Mediated Stroke Therapy – GENTLE/s Approach

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Abstract. Stroke is a leading cause of disability in particular affecting older people. Although the causes of stroke are well known and it is possible to reduce these risks, there is a need to improve rehabilitation techniques. Early studies in the literature suggest that early intensive therapies can enhance patient's recovery. According to physiotherapy literature, attention and motivation are key factors for motor relearning following stroke. Machine mediated therapy offers a great potential to improve the outcome of patients engaged on rehabilitation for upper limb motor impairment. Haptic Interfaces are a particular group of Robots that are attractive due to their ability to safely interact with humans. They can enhance traditional therapy tools, provide therapy "on demand" and can present accurate objective measurements of patient's progression. Our recent studies suggest the use of tele-presence and VR-based systems can potentially motivate patients to exercise for longer periods of time. The creation of human-like trajectories is essential for retraining upper limb movements of patients that have lost manipulation functions following stroke. By coupling models for human arm movement with haptic interfaces and VR technology it is possible to create a new class of robot mediated neuro rehabilitation tools. This paper provides an overview on different approaches to robot mediated therapy and describes a system based on haptics and virtual reality visualisation techniques, where particular emphasis is given to different control strategies for interaction derived from minimum jerk theory and the aid of virtual and mixed reality based exercises.

Keywords

Hemiplegia, Motor Relearning, Robot Mediated Therapy, Virtual Environments, Assistive Technology.

1. Introduction

Cerebral Vascular Accidents (CVAs) often-called "stroke" are caused by a brain attack. Sometimes it might occur when the blood supply is interrupted to a specific area of the brain due to different factors such as a blood clot or other internal bleeding. Due to this interruption some parts of the brain will not receive fresh blood supply needed to maintain oxygen levels for nerve cells survival. Without oxygen nerve cells will die within minutes. Since the brain is the body nerve centre that controls everything we do or think, when nerve cells cannot function part of the body controlled by these cells will cease functioning as well. There are four main types of stroke: two of which are caused by blood clots or other particles, and other two caused by bleeding or haemorrhage. The most common of all strokes accounting for 70-80% are cerebral thrombosis and cerebral embolism [1]. They are a leading cause of disability with estimates of the annual incidence of stroke ranging from 180 per 100,000 in the USA to 200 per 100,000 in England and 280 per 100,000 in Scotland [2]. The incidence rates increase with age, doubling for every 10 years after the age of 45. Approximately one-third of the patients surviving from a stroke are left with severe disabilities [3]. One of the most common motor co-ordination effects after stroke is the Upper Limb (UL) failure to function normally. Close to 85% of stroke patients show an initial deficiency in the UL [4] from whom only 50% of the patients will recover function on their affected UL [4, 5].

Stroke is the third most common cause of death in England and Wales, after heart disease and cancer [6]. Death rates from stroke have been falling throughout this century. For adults aged 16-64 they have fallen by 25% in the last ten years. Recent rates have declined at a slower rate than previously, particularly in the younger age groups [6]. The cost of stroke to the NHS is estimated to be over £2.3 billion. The total cost of stroke care will rise in real terms by around 30 per cent by the year 2023 [7]. England is determined to reduce the death rate from stroke and related diseases in people less than 75 years by at least two fifths by 2010 – saving up to 200,000 lives in total [6].

Following the brain attack the effects of stroke are almost immediate and vary according to the level of damage done in the brain. Some of the most important symptoms include: unexpected insensibility, weakness or paralyses on one side of the body, or in a higher level both sides. Signs of this might be a weak arm, leg or eyelid, or a dribbling mouth, difficulty finding words or understanding speech, sudden blurring, disturbance or loss of vision, especially in one eye, dizziness, confusion, unsteadiness and/or severe headache [1].

Depending on the stroke level, the person will either be admitted to hospital or receive treatment at home. In the early days the aim is to stabilise the condition, control blood pressure and prevent complications. Once the patient is stable, he/she is engaged in an individual rehabilitation programme designed to help him/her regain independence as much as possible. The purpose of rehabilitation is to help the patient to relearn the skills they have lost.

Several authors [5, 8] have shown that the reason why the Upper Limbs (UL) recovery of function is more difficult to achieve than with Lower Limbs (LL) is due to the UL complexity. Upper Limbs are primary task oriented, excluding gesture, non-purposeful movements (e.g. dance, the role in balance and reflex protection mechanisms). These tasks involve UL functions such as, locating a target, reach (transport of arm and hand), grasp an object (grip formation and release) to postural control. Their recovery is of extreme importance in every day manipulative tasks. Treatment is often delivered by means of physiotherapy, which has been accepted worldwide as a routine for patient following a stroke [9].

1.1 Physiotherapy practise

Physiotherapy is inconsistent varying from one therapist to another and from hospital to hospital. Different approaches for treatment techniques have been proposed (e.g. Bobath [10], Cotton & Kinsman [11], Knott & Voss [12], Rood [13]) one of which is focused on motor relearning suggested by Carr & Shepherd [14]. Motor relearning assumes that the performance of motor tasks requires learning. That is, motor control is both anticipatory and ongoing, where postural control limb activities are interrelated. The practice of specific motor skills leads to the ability to perform the task. The task should be practised in the appropriate environment where sensory input modulates the performance of motor tasks. The model is based on the normal motor learning, on the elimination of abnormal movement, feedback, practice and the relationship between posture and movement.

Physiotherapy practice however, is not wholly based on theories or literature research but on the type of approach that the therapist was trained on and the experience gained over the years by working with patients and experts in the field. Based on this many authors depict that there is not sufficient evidence that proves that one treatment is more effective than any other [15]. Recent reviews of Upper Limb post-stroke physiotherapy concluded that the most favourable therapy has not yet been recognised [16, 17]. Nonetheless, several studies [18, 19, 20] tend to point out that UL motor re-learning and recovery levels tend to improve with intensive physiotherapy delivery. The need of conclusive evidence supporting one method over the other and the need to stimulate the stroke patient [15] clearly suggests that traditional methods lack of high motivational content, and objective standardised analytical methods for evaluating patient's performance and assessment of therapy effectiveness.

1.2 Robot mediated therapy approaches

Several authors have already proposed the use of robotics for the delivery of Upper Limb post-stroke physiotherapy. The first far-reaching study on acceptance of robot technology in occupational therapy for both patients and therapists was done by Dijkers and colleagues using a simple therapy robot [21]. Dijkers study reports a wide acceptance from both groups, together with a large number of valuable suggestions for improvements. Advantages of Dijkers therapy include the availability of the robot to successively repeat movements without grievance, as well as, the ability to record movements. However, there was no measure of movement quality and patient cooperation was not monitored.

Studies at the VA Palo Alto Research and Stanford University, USA follow a distinctive approach. Johnson et al. [22] have developed the SEAT: "simulation environment for arm therapy" to test the principle of the 'mirrored-image' by the provision of bimanual, patient controlled therapeutic exercise. The device comprises of a customised design of a car steering wheel equipped with sensors to measure the forces applied by patient's limbs, and an electrical motor to provide pre-programmed assistance and resistance torques to the wheel. Visual cues where given to the patient via a commercial available low cost PC-based driving simulator that provided graphical road scenes. The interface allowed the participation of the patient in the task and the involvement of the paretic limbs in the exercise. The SEAT system implemented 3 different therapy modes: the *passive mode*, *active mode* and *normal mode*. In the *passive mode*, the servomechanism compensates the weight of the paretic limb in order to use their non-paretic limb to guide the paretic limb. *Active mode* is used when the patients demonstrated some level of voluntary control of the paretic limb. In this mode, the servomechanism on the steering wheel encourages the participation of the paretic limb when performing the steering task with the paretic limb while relaxing the non-paretic limb. The *normal mode* was designed to assess the force distribution and analyse the participation of the paretic limb by the participation of both limbs in the steering task and asses the limbs coordination. Recent results suggest that SEAT system increases the interest of patients in using the impaired limb in the steering task and the use of the automated constraint discourages compensatory use of the stronger limb [23, 24].

Based on the same mirror image concept, Lum and colleagues [25] at VA Palo Alto research introduced the MIME: “Mirror-image motion enabler”. A Puma 260 robot was used for the initial MIME prototype, which was attached via a force-torque sensor to the arm splint. In the current prototype a Puma-560 robot replaced the original Puma-260, and it’s paretic limb mobile arm support while a 6DOF digitiser replaced the non-paretic arm support. The MIME system can work in pre-programmed position and orientation trajectories or in a slave configuration where it mirrors the motions of the non-paretic limb. A computer controls movement of the robot, with specific pre-programmed tasks tailored to the subject’s level of recovery and therapeutic goals. Clinical trials with 27 chronic stroke patients (> 6 months post stroke) based on Fugl-Meyer exam, have shown that low compliance systems do not influence negatively the upper limb joint passive range of motion and pain. Results also suggested that robot-aided therapies are safe and effective for neuro development treatment [26].

Rao et al. [27] have used the Puma-260 with a passive and active mode. In the passive mode the robot guided the patient’s arm through a specified path and in the later, the patient leads the robot along a predefined path based on graphical interface resembling a tunnel. If the patient collided with the wall of the tunnel, the robot would then take control and bring the patient’s arm back to the normal path. One of the advantages of this implementation is that the tunnel constraints could be changed according to each individual’s need over the recovery time slot. The results from the test bed implementation of the Puma-260, suggested that the subjects learned to minimise deviations from the center line in repeated trials due to the visual feedback and also, the torque applied to the end-effector became smoother over exercise time.

Work done at MIT by Krebs et al. [28] on the development of a manipulandum that allowed the patient to exercise against therapist nominated stiffness and damping parameters uses a different approach from the systems described so far. Their project defines a new class of interactive, user-friendly clinical device for evaluating and delivering therapies via the use of video games. They have designed and used the patented MIT-MANUS [29] a 3DOF (2DOF active 1DOF passive) planar manipulator to perform a series of clinical trials since 1995 at Burke Rehabilitation Hospital. Reports on initial results with 20 patients with stroke, where 10 used the MIT-MANUS in addition to normal therapy for an additional 4-5 hours a week suggests that they had improved substantially compared to the ones undertaking normal therapy. Recent results were reported [28] from a total of 76 patients assessed for upper limb subsection of the Fugl-Meyer test, motor power for shoulder and elbow, motor status score for shoulder and elbow, and motor status score for wrist and fingers. It was shown that the manipulation of the impaired limb influences recovery, the improved outcome was sustained after 3 years, the neuro-recovery process continued far beyond the commonly accepted 3 months post-stroke interval, and the neuro-recovery was dependent on the lesion location. The MIT-MANUS mechanism however limits the range of possible therapies, has limited data collection facilities and does not allow bimanual therapies as the SEAT and MIME systems.

Reinkensmeyer and his colleagues [30] introduce a different approach with their web-based force feedback telerehabilitator called “Java Therapy”. Java Therapy is an inexpensive robotic telerehabilitation system for arm and hand therapy following brain injury. It consists of a web site with a library of evaluation and therapy activities that can be performed with a commercial force feedback joystick, which can physically assist or resist movement as the user performs therapy. It also allows for some level of quantitative feedback of movement performance, allowing users and their caregivers to assess rehabilitation progress via the web. The *Microsoft Sidewinder Force Feedback Joystick* was used to move the patient’s arm while he interacts with simple 2D games and performs speed, co-ordination and strength tests. Initial comments on this new therapy indicate that while the patient gains concentration, he still does not show great improvement in motor control of the upper arm mainly due to the very small workspace and force feedback provided by the joystick.

So far, the literature reviewed have shown systems and research focused on the rehabilitation of the upper arm. Work in the context of haptic feedback in the rehabilitation of the hand was done at Dartmouth College [31] on an exoskeleton used as a prosthetic device by patients who have lost muscular control of their hand. The device consists of a sensorised aluminium structure attached to the back of the hand wearing a Lycra glove. Position is measured by potentiometers and five cables routed to the palmar side are used to close the index and thumb fingers in a pinch grasp. DC motors located on the forearm caused finger flexion, and restoring springs in the exoskeleton pull the fingers to a neutral position once the actuators are de-energised. Initial tests showed good range of motion, good repeatability but calibration was needed for every new patient, and cable static friction and exoskeleton weight were judged to be too large.

A different system was designed by Popescu et al. [32] for orthopaedic rehabilitation. It consisted of a PC based rehabilitation station with a polhemus tracker, and used the Rutgers Master II glove. They have developed 3 different 3D graphical exercises and 2 functional games (Pegboard and Ball game) from which the patient interacts with. Data is collected into an Oracle database and sent via the Internet to a remote site for analysis. The system is at present ongoing clinical trials at Stanford Medical School.

2. GENTLE/s neuro-rehabilitation approach

The GENTLE/s project is a project financed by the European Commission under the quality of life initiative of framework 5, which aims to evaluate robot-mediated therapy in stroke rehabilitation. The project takes a wide group of users to include patients, family members, physicians, physiotherapists, and healthcare managers. GENTLE/s is focused in neuro and physical rehabilitation and is particularly concentrated in developing new, challenging and motivating therapies to aid the increase of sensory input, relearning stimulation in the brain, achieve functional goals that improve independence and coordination. A more detailed description of the different project phases is given in [33].

The GENTLE/s approach utilises haptic and Virtual Reality (VR) technologies. Haptics studies the way of how to couple the human sense of touch with a world generated by a computer [34]. Initial user needs brain storming sessions and input from members of the Young Stroke Association at Stoke-on-Trent in the UK, have encouraged the group to further develop the idea of using these technologies (haptics and VR) to deliver therapy. A hypothesis that emerged from group discussions is based on the fact that better functional and motor recovery outcomes can be achieved where patients receive a challenging and motivational machine mediated therapy in a context that allows stroke patient to feel comfortable and in control.

2.1 Assumptions

Some studies have shown that repetitive tasks oriented movements are of therapeutic benefit. With the use of haptics and VR technology, patient attention and motivation can be enhanced by means of 'Active Feedback' that will further facilitate motor recovery through brain plasticity [35, 36]. Four different levels for 'Active Feedback' have been identified: visual, haptic, auditory and performance cues. The creation of active agents and biofeedback can be a way of implementing and integrating active feedback in a neuro-rehabilitation robotic system.

- **Visual cues** - In some cases hemiplegic patients following a stroke tend to be confused with what they see [1]. The brain needs to be re-educated to associate (for example) colours and objects to each other. As a result of the need of cognitive re-learning it is important that visual cues be simple, yet stimulating. Visual cues can be represented using real tasks based on the ones used in occupational therapy sessions, to realistic and accurate goal oriented 3D computer environments. This can be anything from a virtual room, a virtual kitchen, museum, to an interactive game, etc.
- **Haptic cues** - Kinaesthetic feedback can help to discriminate physical properties of virtual objects, such as geometry. It can also be used to deliver physical therapy to a human subject using haptic interfaces. The force delivered in this way can be very therapeutic dependent on the way we apply this force to human muscular and skeletal systems. It will undoubtedly play an important rule when manipulating objects, either virtual or real. In conjunction with interactive virtual and augmented tasks, it can simulate the shape of a virtual pen, bingo card or the friction/drag when writing on the virtual bingo card.
- **Auditory cues** - Everyone in today's society enjoys to be acknowledged upon successful completion of a task. Thus way encouraging words and sounds can be played when the patient is trying to perform a task, congratulatory words when a task was achieved with success and comforting words when the task wasn't achieved.
- **Performance cues** - As human beings we tend to improve ourselves by comparing our actions to others that we consider a model in society. In an academic context, a student uses feedback given by his lecturer on an assignment to improve his weak points on the subject. Similarly, in a haptic stroke rehabilitation system, results of the previous tasks can be displayed stating the errors committed and the level of help obtained to complete the task. Performance cues should however, be delivered in a constructive way.

A robotic/haptic rehabilitation system should be ergonomically comfortable. The therapy should be enjoyable and the system should be able to nourish the patient's trust by developing a sense of friendship and companionship between the patient and the system. Such a concept can be achieved by the introduction of a personality to the system such as, a character (wizard) that interacts with the patient by using different identified cues. Different wizards can be implemented for different personalities. These are defined and assigned to the patient once the therapist has found out what their interests are.

An example could be in the case where the patient is performing a simple exercise such as, reaching for an object in a virtual world. In this case with the aid of a good sensor system analytical measures can be obtained in order to identify if the patient is struggling in reaching the target. Taking this into account, the wizard could then pop up and encourage the patient to finish the movement. Another scenario could be the presentation of the score at the end of the session. Yet another possible variation of the wizard could be one, which is able to play a game of checkers, domino, etc., against the patient.

The wizards form an implementation of visual, auditory and performance cues. They can be of the form of cartoons, 3D models of humans or any other form, such as pre-defined animations. The ideal wizard is the one that interacts with the patient while the patient performs the required task. The wizard can be an entity based on artificial intelligence knowledge databases, which can promptly interact with the patient in real-time.

2.2 Current prototype

The current prototype system (figure 2.1) consists of a frame, a chair, a shoulder support mechanism, a wrist connection mechanism, an elbow orthosis, two embedded computers, a large computer screen with speakers, an exercise table, a keypad and a 3DOF haptic interface (HapticMaster from FCS). The patient is seated on the chair with his/her arm positioned in an elbow orthosis suspended from the overhead frame. This is to eliminate the effects of gravity and address the problem of shoulder subluxation. The wrist is placed on a wrist-orthosis connected to the haptic interface using a quick release magnetic mechanism. At this point, the physiotherapist can select the patient profile from the database, select an exercise or create a new exercise using a 3D graphical user interface. The setup exercise (figure 2.2) allows the therapist to define the exercise path, amount of help needed for each segment of the exercise, duration of the movement for each segment, the 3D context of the virtual exercise environment. When the exercise definition has been saved, and the exercise is selected, the system is ready to perform that exercise with the patient.

FIGURE 2.1 The GENTLE/s system.

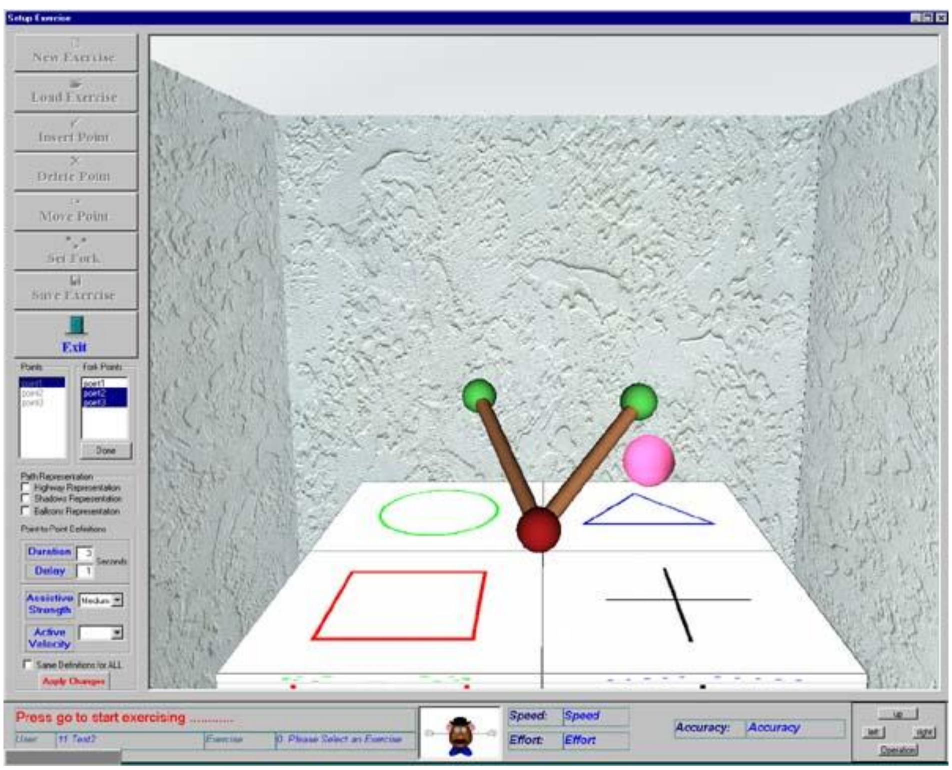

FIGURE 2.1 Setup exercise allows the therapist to define the exercise path. Here a fork exercise is shown (further explained in section 3.1.4).

2.3 Exercises & movement guidance

In the current prototype, 3 different Virtual Environments can be used (figure 2.3):

1. Empty room – A simple environment that represents the Haptic Interface workspace and intends to provide early post-stroke patients with awareness of physical space and movement (figure2.3 (a)).
2. Real room - An environment that resembles what the patient sees on the table in the real world. The mat with 4 different shapes that is on the table (figure 2.1) is represented in the 3D graphical environment (figure 2.3 (b)). This environment was developed to help discriminating the 3rd dimension that is represented in the Monitor 2D screen.
3. Joaquim's room - A high detail 3D environment of a room comprising of a table, several objects (a book, can of Pepsi), portrait of a baby, window, curtains, etc (figure 2.3(c)).

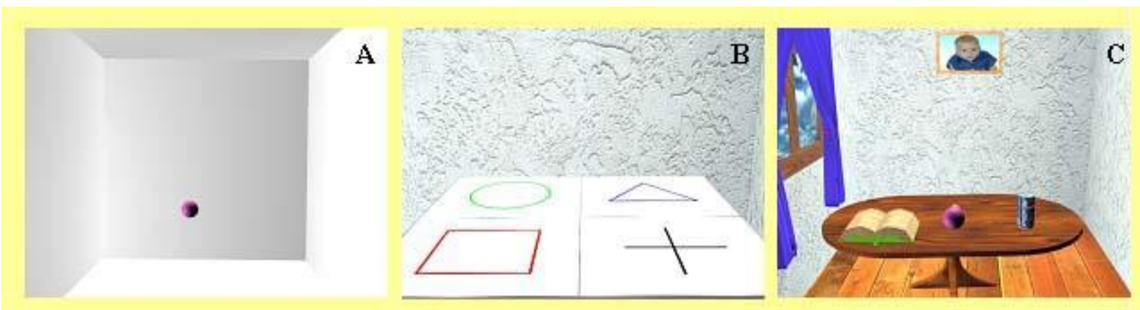

FIGURE 2.3 (A) Empty room, (B) Real room, (C) – Joaquim's room.

In order to allow the user to navigate and interact with a virtual/real task, several mathematical models have been implemented (further explained in section 3) as a control strategy capable of correcting the patient's movement. An operation button must be continuously pressed by the user on the keypad (figure 2.1) to allow for the device to assist in the movement. Since movement control was defined to be in between two points, a new concept was introduced. The 'Bead Highway' concept assumes that movement takes place in between a start point and an end point. It is assumed that its behaviour is similar to the behaviour of beads on a string, they can only move along their pathway. To achieve this behaviour the endeffector is connected to a virtual spring and damper (figure 2.4) where the bead is constrained to move along a 'wire-highway' that defines both the path and the velocity profile of the movement.

Deviations from the movement profile are permitted but constrained depending on the restoring force of the spring and associated damper. Different levels of guidance and correction can be programmed, for different patients with different recovery levels. For a patient in early days after stroke, more help is needed to move along the pathway and this behaviour can be achieved by implementing a velocity profile for the bead on the highway and proper spring-damper combination for more assistance. For a patient who has more motor functions recovered, we may need a different velocity profile along the pathway and a different setting defined for the spring--damper behaviour.

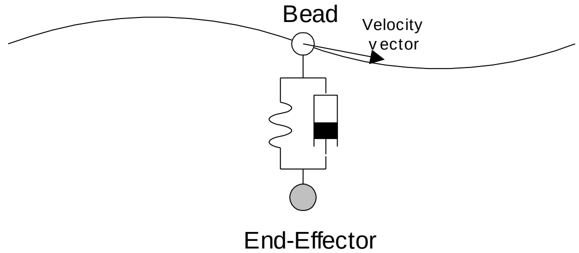

FIGURE 2.4 Spring and damper combination – Bead Highway.

Figure 2.5 shows the representation of the path (highway), where in part (A) of the figure it can be seen the start point (yellow), the end point (blue) and the desired trajectory between these two points (highway). The choice of colours addresses the problem of colour blindness that some primary colours such as, green and red caused to some patients in earlier studies [37] In part (B) of figure 2.5, shadows and balloons are used to help perceiving the depth and height of the positioned points with respect to the table on the screen.

(A) (B)

FIGURE 2.5 Representation of a movement trajectory in the virtual environment.

3. Implementation of different therapies

Many different studies have agreed that it is of extreme importance that a clear understanding of how the human arm moves is achieved to supplement interaction in between a machine and a human subject. The urge to understand human dynamics with emphasis on explaining how human's brain plans for reaching movements was first studied by Bernstein in 1967 [38] and later by Bizzi and colleagues in 1984 [39]. This thirstiness to understand human movement lead to the study of several kinematic [40, 41], dynamic [42], and neural features [43] of the human arm reaching movements. In most of these studies, one characterisation of multi-joint planar reaching movements was found to be a straight path with a bell shaped velocity profile mapped [41, 42, 44, 45]. The studies described on the literature suggested different optimisation models based on kinematic, dynamic or neural terms. An overview of these optimisation models and techniques can be found in [46, 47].

The empirical minimum jerk approach is the simplest to implement in a real-time system and such model was first purposed for a single joint by Hogan [40] and further developed for multi-joint movements by Flash and Hogan [48]. The later states that humans by nature tend to minimise the jerk parameter over the duration of the reaching movement of the arm. Jerk is intrinsically the rate of the change of acceleration with respect to time, namely the third time derivative of the position. Minimum jerk theory states that any movement will have maximum smoothness when the J parameter given by equation (1) is minimised. Where *d* is the duration of the movement and *x* is the hand position at time *t*.

$$J = \int_0^d \left| d^3x/dt^3 \right|^2 dt \tag{1}$$

3.1 Theoretical models

The models presented in this paper are based on the use of polynomials to control position, velocity and acceleration parameters encountered on a human based movement profile. The use of polynomials has enormous advantages for use in real-time applications, particularly in rehabilitation. Using this methodology, control of human trajectory is enhanced by the flexibility of being able to redefine polynomials or superimposing a new trajectory over the previous one in real-time.

3.1.1 Minimum jerk point-to-point model

The first model is based on the assumption that every single movement happens in between a start point and an end point, from which a straight-line path is generated (figure 3.1).

In this case it is advantageous to have accelerations that are zero at the start and end of the movement. For this a parameter τ is chosen such that:

$$-1 \le \tau \le 1$$

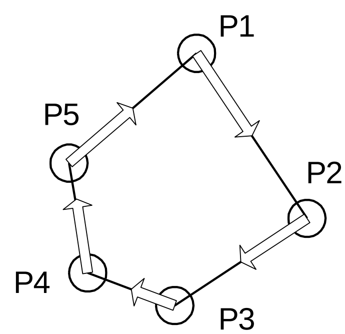

FIGURE 3.1 Point to point movement definition

This parameter (τ) in a later stage can be scaled to the movement exact time. Symmetrical movements have a mid range position, velocity and acceleration occurring when $\tau = 0$ which in turn eases the calculation of the polynomial coefficients at a later stage. To ensure that the acceleration at the start and end is zero, a polynomial with odd power is used. In the literature [41] a 5th order polynomial has already been used. However, in order to allow for non-symmetric, non-minimum jerk polynomials to coexist with symmetric minimum jerk polynomials, a 7th order polynomial is used:

$$p = a + b\tau + c\tau^2 + d\tau^3 + e\tau^4 + f\tau^5 + g\tau^6 + h\tau^7 \tag{2}$$

The derivatives with respect to the parameter (τ) are denoted as the more familiar p', p'', p'''. The following identities are constraints applied to the start and end of the movement:

Start and end positions are defined:

$$p\big|_{\tau=-1} = p_{start} \qquad p\big|_{\tau=1} = p_{end}$$

Start and end velocities and accelerations are zero:

$$p'|_{\tau=-1} = 0 \qquad p'|_{\tau=1} = 0$$

$$p''|_{\tau=-1} = 0 \qquad p''|_{\tau=1} = 0$$

Hence, the polynomial becomes:

$$p = a + b\tau + d\tau^3 + f\tau^5 + h\tau^7 \tag{3}$$

We can then identify the coefficients of the polynomial as:

$$a = \frac{(p_{start} + p_{end})}{2} \tag{4}$$

$$b = p'|_{\tau=o} = v_{mid} \tag{5}$$

$$d = \frac{35}{16}\Delta_p - 3b \tag{6}$$

$$f = 3b - \frac{21}{8}\Delta_p \tag{7}$$

$$h = \frac{15}{16}\Delta_p - b \tag{8}$$

Where:

$$\Delta_p = p_{end} - p_{start} \tag{9}$$

Mid velocity needs to be determined in order to minimise the integral given by equation (10) and achieve a minimum jerk movement.

$$J = \int_{-1}^{1} |p'''|^2 d\tau \tag{10}$$

Thus, to achieve maximum smoothness, mid velocity should be expressed by:

$$b = \frac{15}{16}\Delta_p \tag{11}$$

If equations 8 and 11 are used, due to the minimum jerk movement the polynomial is reduced to a 5th order polynomial. The minimum jerk model and polynomials presented in this section were used to implement the therapy modes explained in section 3.2 and to generate minimum jerk paths for the Bead-Highway explained in section 2. Polynomial coefficients are calculated between Haptic Interface end-effector's current position (P1 in Figure 3.1) and target's position (P2 in Figure 3.1).

3.1.2 'Up and Over' model

Often rehabilitation exercises involve the recovery of function for actions involving lifting and transporting an object from one location to another. Such curvilinear non-minimum jerk movement pattern requires an even order polynomial (equation 12) for the vertical axis of the movement:

$$p = a + c\tau^2 + e\tau^4 + g\tau^6 \qquad (12)$$

In order to elevate the trajectory by amount of H and go back to the start point, these additional assumptions are made:

Start and end positions are the same:

$$p_{start} = p_{end}$$

Movement is symmetric:

$$a = p\big|_{\tau=0} = p_{start} + H$$

Hence the polynomial coefficients become:

$$g = -H \qquad 13)$$

$$c = -3H \qquad 14)$$

$$e = 3H \qquad 15)$$

3.1.3 Super-positioning model

Certain movements however, are not straight-line movements. These can be movements such as placing cubes on top of each other or placing a book on a shelf.

For this, a technique comparable to the one used by Flash and Henis [41] whereby movements that are not straight-line or non-symmetrical by nature are achieved can be used. It consists of superimposing two distinct trajectories to create a third one.

If two different polynomials are given:

$$p = a + b\tau + d\tau^3 + f\tau^5 + h\tau^7 \qquad 16)$$

$$q = a + c\tau^2 + e\tau^4 + g\tau^6 \qquad 17)$$

A different trajectory can be created by adding polynomials on equations 16 and 17 vectorially (figure 3.2):

$$h = p + q \qquad (18)$$

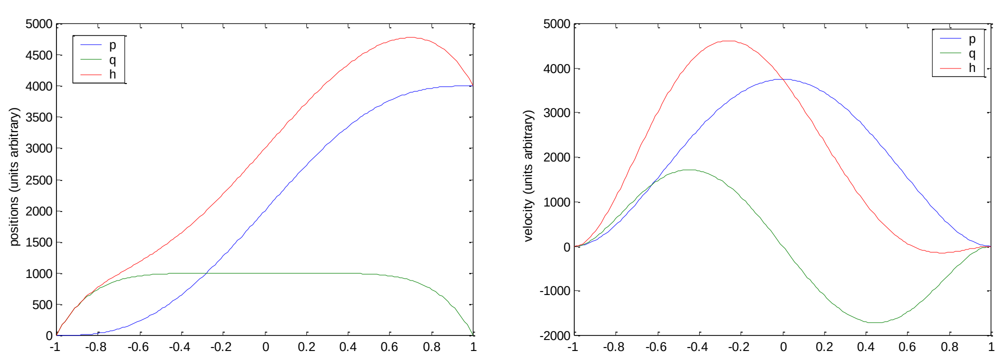

FIGURE 3.2 Super-positioning model.

(Left) – superimposed positions; (Right) – superimposed velocities.

The super-positioning model allows for smooth trajectories to be achieved when the minimum jerk parameter for equations (16, 17) is minimised separately. In this case the parameter (τ) for the input polynomials can be mapped to time differently, therefore the second trajectory (equation 17) does not need to begin at $\tau = -1$.

3.1.4 Fork model

The Fork model was created with the intention of augmenting the existing therapy models by allowing the user to have the freedom to decide which target to choose from. Comparing this model to the point-to-point model, the only difference is that movements are not generated sequentially (i.e. from P1 to P2, P2 to P3, etc.) but instead the user is able to decide if it is more appealing to move from P1 to P2 or from P1 to P4 (figure 3.3 (A)).

For example, in a score based exercise, it could be that P2 is closer in distance to P1 than P4 and therefore P4 is worth more points when compared to P2. In this case it is obvious that if the user wants to score higher, he/she has the chance to choose the movement with higher score. In a clinical point of view, apart from providing the stroke patient with repetitive challenge therapies, the ability to 'choose' can be motivational and be of therapeutic benefit.

The fork model uses the force readings provided by force sensor mounted on the end-effector of the haptic interface to identify the target that the patient wants to select. Once the user attempts to move in the direction of his/her chosen target, the vector dot products are used to detect the direction and the amount of force exerted by the user in the direction of the target point (figure 3.3 (B)).

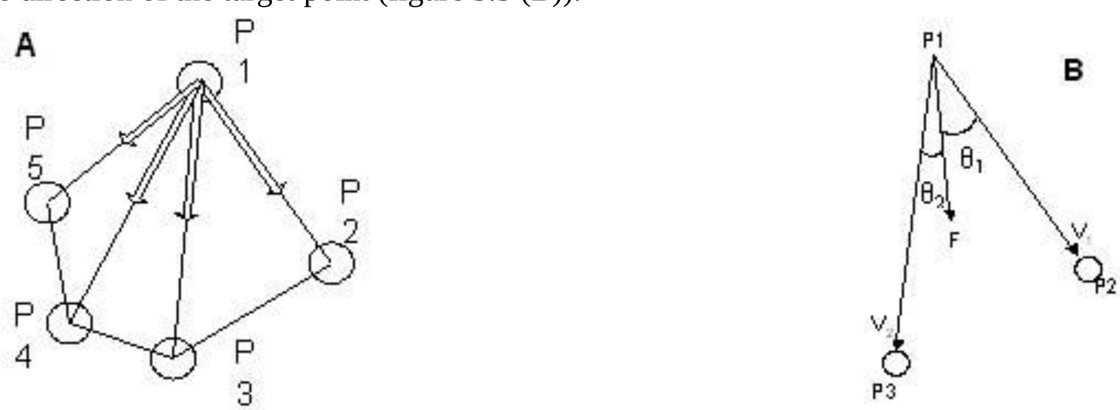

FIGURE 4.3. Fork model. (A) Target selection; (B) Vector dot products

Vector dot product of two matrix, shows the projection of one vector on to the other, and by projecting the user's force vector, on to vectors $\vec{V_1}$ and $\vec{V_2}$, we can detect which target is selected by the user. We Know that:

$$\vec{V_1} = p_2 - p_1 \qquad 19)$$

$$\vec{V_2} = p_3 - p_1 \qquad 20)$$

If the user is exerting a force $\vec{F}$ on the haptic interface, then θ_1 and θ_2 can be estimated as:

$$\cos\theta_1 = \frac{\vec{F}.\vec{V_1}}{\left|\vec{F}\right|\left|\vec{V_1}\right|} \qquad 21)$$

$$\cos\theta_2 = \frac{\vec{F}.\vec{V_2}}{\left|\vec{F}\right|\left|\vec{V_2}\right|} \qquad 22)$$

It is also know that, if both vectors are in the same side of the plane normal to the force applied, then $\cos\theta_1 \geq 0$, and $0 \leq \theta_1 \leq \pi$. Thus the algorithm for detecting the target becomes:

Step 1 – Calculate $\vec{V_1}$ and $\vec{V_2}$ using equations (19, 20)

Step 2 – Calculate $\cos\theta_1 \geq 0$ and $\cos\theta_2 \geq 0$ using equations (21, 22)

Step 3 – IF $\cos\theta_1 \geq 0$ OR $\cos\theta_2 \geq 0$ AND $\vec{F} \geq F_{Activation}$ (a defined threshold value) then:

Step 3.1 – IF $\cos\theta_1 \geq \cos\theta_2$ then $\theta_2 \geq \theta_1$ which means "target P2 is selected"
ELSE IF $\cos\theta_2 \geq \cos\theta_1$ then $\theta_1 \geq \theta_2$ which means "target P3 is selected"
Step 3.2 – Initiate minimum jerk trajectory to appropriate target.

In order to find the target between more than two points, the algorithm becomes to find the maximum positive value for *cos* (q_i) where i is the index number assigned to targets on the fork junction.

3.1.5 Time mapping model

The parameter (τ) provides a useful scaling way on the polynomial implementation. This parameter can be scaled to time using a linear scaling or quadratic, which in turn allows for different movements to be attained depending on the scaling factor. In this context, equation (23) can be used to scale time (t) to (τ) linearly with respect *to* $t_{Start} = 0$ *and* $t_{End} =$ *duration.*

$$1 + \left(\frac{2}{t_{end} - t_{start}}\right) * \left(t - t_{end}\right) \qquad 23)$$

Different time mappings are possible, for example a quadratic mapping can be used:

$$\tau = at^2 + bt + c \qquad 24)$$

Where:

$$0 \leq t \leq duration \qquad 25)$$

Hence the coefficients for this quadratic become:

$$c = -1 \tag{26}$$

$$a = \left(\frac{2}{d^2} - \frac{b}{d}\right) \tag{23}$$

Figure 3.4 shows a comparison in between linear and non-linear mapping (*b=1*) of parameter (τ) for both positions and velocities.

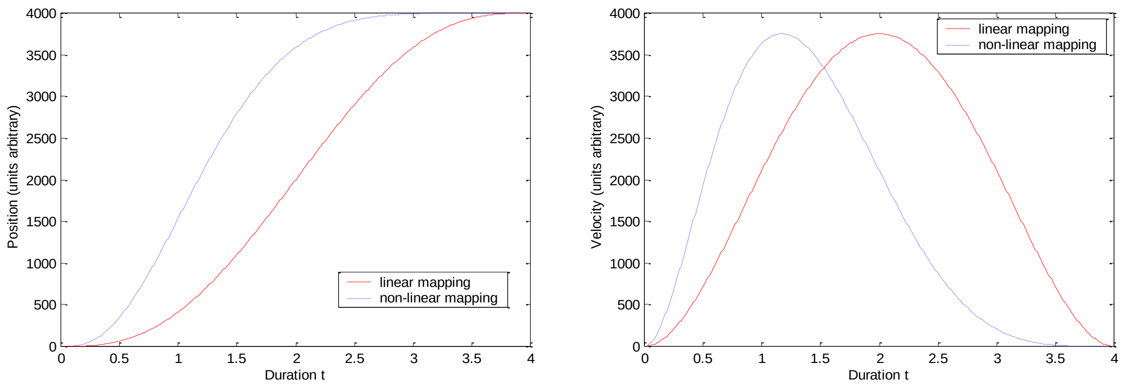

FIGURE 3.4 Time mapping model.

(Left) – time mapped positions; (Right) – time mapped velocities

3.2 Different therapy modes

Using the minimum jerk polynomials three different therapy modes are implemented on the GENTLE/s system:

3.2.1 Patient Passive mode

The *Patient Passive mode* was the first therapy mode implemented. As the patient lacks the power to initiate the movement, remaining passive, the haptic interface will move his arm along the pre-defined path. When patient's arm reaches to the target, depending on the exercise selected, the movement can be reversed back to start position or continued towards the next defined position.

3.2.2 Patient Active Assisted mode

Second mode is *Patient Active-Assisted* mode. In this mode, robot starts moving as soon as the patient initiates a movement in the direction of the highway. Robot initiates the movement when $F_{User}.U > F_{Activation}$. Where U is the position vector between the start point and the end point. After the initiation is made, robot helps the user to reach to the end point.

3.2.3 Patient Active mode

Third mode is *Bead-Highway (ratchet)* mode or *Active* mode. The velocity profile for this mode was set to zero to provide unlimited time for the patient to finish the correct task. This mode provides a unidirectional movement, where the amount of deviation can be controlled by changing spring-damper coefficients. Similar to the previous mode, the user initiates the right movement. The haptic interface stays passive until the user deviates from the predefined path. In this case, the spring-damper combination encourages the patient to return to the highway. This operation can end by reaching to the end point or releasing the operation button. Upon arrival to the end point, it is up to the user to continue the same movement back to the start point, a new point or end the whole session in this mode. To implement this mode, a 'ratchet' or energy function was calculated so that the user can only move towards the movement goal. The ratchet function relies on the actual position of the robot p' and the position of the bead p to calculate an energy. Thus at a particular setting of the parameter t the energy would be $E(t) = (p(t) - p')^2$.

When user moves along the path, if the movement involves less energy then that position is accepted at the current position of the bead on the highway, otherwise, the virtual spring damper will resist user's movement to higher energy states. This means, if $t=t_1$, then for $t_2>t_1$, $E(t_1)$ and $E(t_2)$ are calculated, if $E(t_2)<E(t_1)$ then t is adjusted to be the new value t_2. This algorithm has the effect of only allowing one-way movement along the highway.

4. Undergoing Clinical trials

A pilot study was carried out and a principle study is undergoing with 2 prototypes since autumn of 2001. The choice of sites in both the UK and Ireland gives the study access to a greater number of subjects (30 in total) for inclusion in the clinical trials. In Dublin the studies are being conducted at the Adelaide and Meath Hospital, a teaching hospital of Trinity College, Dublin and in the UK at the Royal Berkshire Hospital. Some of the initial results of the pilot study are published [37] with more detailed results of the principal clinical trial to be published in the near future. Initial pilot studies on patient's visual perception, force feedback effects, and motivational aspects of using haptic interfaces have already been presented [37]. Some of the initial pilot studies have shown that the majority of the patients were enthusiastic towards the use of visual and haptic cues. The trial suggested that the system as a whole is able to motivate hemiplegic patients and encourage them to participate and exercise more. Currently the group is considering outcome measurements and methodologies.

5. Conclusion

In this paper we have introduced the GENTLE/s neuro-rehabilitation approach, which is based on Haptics and Virtual Reality technologies to deliver challenging and motivating therapies to upper limb impaired stroke patients.

A broad mathematical framework has been established to compute natural path for machine-assisted movements using Virtual Environments. We have demonstrated that, using the 'Bead highway' the path of movement can be corrected and traversed in several ways.

Currently 2 identical prototypes are undergoing clinical trials in the UK and Ireland with 30 stroke patients, from which clinical outcome measures are to be published in the near future.

A second prototype is under development to improve the current prototype at hardware and software levels.

Acknowledgements

The work presented in this paper has been carried out with financial support from the Commission of the European Communities, Framework 5, specific RTD programme "Quality of Life and Management of Living Resources", QLK6-1999-02282, "GENTLE/S – Robotic assistance in neuro and motor rehabilitation". It does not necessarily reflect its views and in no way anticipates the Commission's future policy in this area.

We are grateful to all our colleagues in the GENTLE/s consortium (University of Reading, UK; Rehab Robotics, UK; Zenon, Greece; Virgo, Greece; University of Stafordshire, UK; University of Ljubljana, Slovenia; Trinity College Dublin, Ireland; TNO-TPD, Netherlands; University of Newcastle, UK) for their ongoing commitment to this work.

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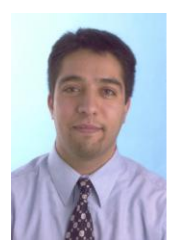

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