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# Investigation of a Mechatronic Device for the Remedial Treatment of Brain Injured Children

*Thesis submitted to Middlesex University in partial fulfilment of the requirements for  
the degree of Doctor of Philosophy*

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*For the Brain Injured Children,  
their Families and Carers*

## ABSTRACT

To speed the recovery of brain injured children using the method of patterning; it must be made efficient. Efficiency can be achieved by automating the manual method, which will provide the patients with the necessary stimuli needed to help them enhance/restore their natural mobility.

This thesis describes research into a novel moderate-cost single-axis Mechatronics device for the remedial treatment of brain injured patients. The device will enhance and/or improve their natural mobility by stimulating the undamaged brain cells responsible for mobility in the central nervous system through physical activity.

A detailed review of rehabilitation robotics was undertaken, covering more than seventy projects relating to disabled people. This review helped to identify the main areas of this research regarding the most suitable structure of the machine and setting up the design specifications for the device. A critical investigation of past and present patterning machines and workstations helped avoid the mistakes made by previous designers in not including brain-injured patients in the initial stages of the design. Use of high technology video equipment has made practicable the development of mathematical expressions based on experimental data for the movements of human arms, feet and head.

Measurements taken and ergonomic data used made it possible to implement a realistic practical novel kinematic arrangement for the patterning machine. A thorough review of direct drive electrical actuators, and surveys and measurements of the human body with respect to the kinematic arrangements, resulted in the selection of the most appropriate actuator for each axis. The selection of the motor and gearbox was based on the mass of each part of the human body in the prone position, the criteria of high peak torque to motor ratio, low cost, minimum maintenance, safety and compatibility.

A computer model of the kinematic arrangement designed was created including the necessary motion constraints, using ADAMS and 3D Working Model simulation packages to test, verify and analyse the static and dynamic stability of the kinematic arrangements and the force interaction between the system and the patient. The simulation results led to some modification in the design regarding the kinematics and dynamic stability of the system by varying different design variables. A walking model of a human was created to simulate the real patient. The model was placed on two units where the feet were the only contact points with the moving belts; the model torso was supported by a harness to hold it in the upright standing position. The results obtained showed the movements of both feet (knees, hips and ankles) in addition to the right and left elbows.

The system hardware was designed and implemented using custom-made safety critical software to control the device to carry out the desired tasks. Safety is considered to be one of the main issues that this research program has developed and implemented. An optimal control strategy was developed to drive the prototype. Smooth movements of the system were achieved through a PD control system enhanced with velocity feed forward gain with position accuracy of  $\pm 0.168$  mm. The desired positional accuracy of the Patterner Machine was  $\pm 0.632$  mm.

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## GLOSSARY OF ABBREVIATED TERMS

---

- AIAHP - The Institute for the Achievement of Human Potential
- BIBIC - The British Institute for Brain Injured Children
- BRU 100 - Motor Drive
- CNS - Central Nervous System
- CrosCLE - Cross Creep Left Elbow
- CrosCLL - Cross Creep Left Leg
- CrosCRL - Cross Creep Right Leg
- HomCRL - Homolateral Creep Right Leg
- HomCLL - Homolateral Creep Left Leg
- HomCRE - Homolateral Creep Right Elbow
- HomCLE - Homolateral Creep Left Elbow
- HomCrRL - Homolateral Crawl Right Leg
- HomCrLL - Homolateral Crawl Left Leg
- HomCrRE - Homolateral Crawl Right Elbow
- HomCrLE - Homolateral Crawl Left Elbow
- Lankle - Left ankle
- Lelbow - Left elbow
- Lknee - Left knee
- Lhip - Left hip
- Rankle - Right ankle
- Relbow - Right elbow
- Rknee - Right knee
- Rhip - Right hip
- PAICEMD - Peto Andras Institute for the Conductive Education of the Motor  
Disordered
- P - Proportional control
- PD - Proportional Derivative control
- PI - Proportional Integral control

PID - Proportional Integral and Derivative control

PWM - Pulse Width Modulation

.  $L_B$  - Length of Belt

$J_L$  - Inertia at input shaft

$J_P$  - Inertia of pulleys

$J_B$  - Inertia of Belt

PM - Permanent Magnet Motor

RSL - Road Safety Laboratory

RAID - Robot for Assisting the Integration of the Disable

## GLOSSARY OF MEDICAL TERMS

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Hypotonia - Having lower osmotic pressure of cells, which effects the normal quantity of fluids in a particular cell.

Aetiology - The medical study of causation of disease.

Polyneuritis - Stimulation; Inflammation of several nerves.

Dystrophia - Disorder of the muscle tissues.

Myotonia - Undertension of the muscle.

Polymyositis - Inflammation of several muscles at the same time.

Myasthenia Gravis - Chronic progressive disease in which the muscles become fatigued with progressive muscular paralysis.

Myopathy - Mental sensitivity or receptiveness.

Paresis - A diminished activity of a function.











# Chapter 1

## INTRODUCTION

---

*'There must be a beginning of any great matter, but the continuing unto the end until it is thoroughly finished yields the true glory.'* Sir Francis Drake, (1540 - 1596)

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### 1.1 BACKGROUND

#### 1.1.1 Brain Injury

A Brain Injured person is defined as someone who began to develop a normal brain but later suffered an injury to the brain which resulted in the damage of one or more brain cells [Pennock, 91]. In the past, the consequences of brain injury were considered to be untreatable. The term cerebral palsy is most commonly used to describe brain injury and the condition accompanying it. Cerebral palsy may be medically defined as a persistent, but not unchanging, disorder of movement due to non-progressive disease of the brain in the early life of the patient [Bartrop, 87]. Brain injury or mental retardation is often accompanied by hypotonia in infancy (cell shrinkage, i.e. the subject has lower osmotic pressure which effects the quantity of the solution in the cells) and this is combined with delayed motor development. Mongolism, or Down's syndrome as it is medically known, exemplifies a situation of neuromuscular disease. These conditions of varied aetiology (the medical study of causation of disease), pathology and severity are grouped together because they raise problems of management and treatment common to all. Hypotonia is common early in the evolution of cerebral palsy, where the subject has involuntary movements and spastic diplegia. Other causes of brain injury are infantile polyneuritis (inflammation of several nerves), spinal cord injuries during delivery, spinal cord compression,

congenital dystrophia myotonica (under tension of muscle tissues), polymyositis (inflammation of several muscles at the same time), congenital myasthenia gravis (chronic progressive disease in which the muscles become fatigued with progressive muscular paralysis), congenital muscular dystrophy (disorder of muscle tissues) and certain other rare myopathies (mental sensitivity or receptiveness) [Barltrop, 87]. Motor function in cerebral palsy may be impaired as a result of paresis, abnormal tone, involuntary movements, incoordination or persistence of primitive reflexes (earlier stages of development). The dysfunction may involve one, two, three or four limbs in a variety of combinations. Classification is therefore usually based on the predominant type of motor dysfunction and also in terms of severity and associated effects.

The brain damaged infant is often apathetic, socially unresponsive and subject to fits. In most severe cases, cerebellar patients can no longer walk without firm support. However, these severe cases retain the ability to produce functional responses either by patterning or any other means.

With the passage of time and technological advances, treatments are being developed. The precise nature of the treatment adopted by a specific organisation generally varies due to the fact that no standardisation has yet been reached on definitive details of treatment, although the general principles used by these different organisations are similar.

### **1.1.2 Is It Possible to Recover from Brain Injury?**

Recovery from brain injury or brain damage depends on the behavioural adjustments as well as the structural adjustments in the brain, i.e., patients usually have problems using their skills and usually benefit from the guidance and the instructions of a therapist and also may train additional skills as the brain makes structural adjustments. One area of structural recovery is the restoration of functional duties for the uninjured neurones (cells that receive and send messages throughout the nervous system), within a few hours of brain injury, toxins spread and causes a decline in behaviour, after

several days or weeks the toxins are washed away and the blood supply becomes normal which results in an improvement in behaviour [Olsen, 1986].

Another way for recovery is to repair injured neurones. Healthy neurons often have synapses (a junction between two neurones) which can be activated when other synapses are destroyed [Merzenich et al., 1984]. In addition, other neighbouring neurones can find new branches to re-route the transferred information [Sabel, 1984]. The safest way of recovery at present is to use physical activities to train the undamaged brain cells rather than using other methods such as grafting of brain tissue [Gash, 1985], direct intervention in the brain [Kalat, 1988] or the use of chemicals to promote sprouting and increased sensitivity [Sabel, 1984].

### 1.1.3 Brain Injury Institutions

There are many organisations that treat brain injured children world wide. Among them are three prominent institutions. These are:

- 1) The Peto Andras Institute for the Conductive Education of the Motor Disordered in Hungary (PAICEMD), which was founded by Dr. A. Peto in 1952 (originally known as the National Motor Therapy Institute) although his work was only officially recognised in 1963.
- 2) The Institute for the Achievement of Human Potential (AIAHP) in the United States of America founded by Dr. G. Doman in 1962. AIAHP was founded to promote the Doman-Delacato method of therapy (known in the UK as the bench method) which was developed by Glen Doman and Carl Delacato, both of whom were greatly influenced by the work of Dr. Temple Fay, a neurosurgeon. Both were dissatisfied with the results of conventional rehabilitation therapy and had begun to focus their attention on the treatment of the brain injured.
- 3) The British Institute for Brain Injured Children (BIBIC) in the United Kingdom, which was founded in 1972 by Mr. J. K. Pennock. BIBIC follows closely the principles of treatment established by Doman-Delacato with some modifications.

### **1.1.4 Available Treatment**

The methods devised by these prominent institutes for imparting remedial treatment to brain injured patients are largely manual, using simple aids whenever possible to assist with carrying out the desired techniques. Presently, the most frequent methods of treatment used are Doman-Delacato (bench method) and Conductive Education. Most of the other methods of treatment are based on the following outlined methods.

#### ***1.1.4.1 Doman-Delacato***

Doman-Delacato is a technique based on the theory that the brain, like a muscle, will grow if given regular exercise. This exercise, however, must follow a particular pattern based on an evolutionary pathway. Doman teaches that brain damage, caused by a non-progressive injury to the brain such as in cerebral palsy, can be alleviated by therapeutic programmes based on the re-learning of early experiences, such as creeping and crawling [Doman, 60]. This stimulates dominant areas of the brain, encouraging them to take over the functions of those parts that have been damaged or lost (dead). This is achieved by providing the patient with the kind of stimulation (patterning) that a normal infant would experience in order to stimulate the undamaged brain cells. As ordinary stimulation is insufficient to produce responses from the undamaged brain cells, the stimuli are increased significantly in terms of their frequency, intensity and duration. Since these patterning techniques are extremely labour intensive, they need to be carried out during a period of several hours per day, in most cases for several months or even years until an improvement is noticed. It is therefore disadvantageous to the patient and difficult, if not impossible, to arrange for at least four helpers plus one of the parents to carry out the techniques for a large sized patient and three helpers for a small sized patient. Furthermore the helpers themselves will experience limitations imposed by fatigue and emotional stress.



#### ***1.1.4.2 Conductive Education***

Conductive Education is a teaching and learning system designed to enable children and adults with disabilities to function more independently. It was developed in Hungary, but British therapists and teachers have used elements of the system for over 20 years. Conductive education may be appropriate for children and adults who have motor disorders. In other words, those who have problems with movement because of damage to areas of the central nervous system that is responsible for organising motor functions. Although this method may not be suitable for everyone and it is not a cure for their condition, but it may still enable them to overcome their disorders and function independently.

#### **1.1.5 Proposed Solution**

The existing manual method of treatment is a labour intensive technique that requires a team of up to five people to carry out the patterning for an average sized patient and a team of three persons for a patient of a small size (6 months to two years old). Since humans can not carry out the techniques with the accuracy and efficiency needed to achieve favourable results and the fact that finding at least four helpers at one time on a regular basis is often difficult if not impossible. This research program proposes to carry out the existing method of patterning with a machine using the technological advances in the fields of Mechatronics and robotics. This Pattermer Machine shall carry out the techniques of patterning that were specified by the British Institute for Brain Injured Children with some modifications, i.e. the machine shall provide real creep and crawl movements. This invention aims to provide mechanised manipulation [Kavina, 92] of body joints associated with major muscle groups for brain injured patients to compensate for muscle and nerve incapacitation. It is also set to provide new stimulated information to the healthy cells of patient's brain through effective and controllable continuous joint activation. Kavina, 96 has proposed the use of conveyor belts as a possible solution and replacement for the currently manual bench method.

A project of such a scale requires a team effort, involving patients, operators and programmers. Investigations into the use of robotics in rehabilitation, human factors, ergonomics and disability were undertaken.

## **1.2 REHABILITATION TAUTOLOGY MECHATRONIC**

Applications of robots have always been focused on the automotive industry and consequently much of the early research work was directed into this area. Recently however, there has been a steady growth in research in the areas of medical technology and rehabilitation robotics. The impetus for this growth stems from the fact that each year an estimated two million of the world population of new born babies are born brain injured [Ferriman, 94] and the fact that every 15 seconds in the United States, someone suffers a brain injury [Rehab, 97]. These reasons together with public awareness of these facts and the availability of funds for research, has meant that more emphasis was placed on developing rehabilitation robotics to help significantly improve the lives of the disabled and brain injured patients in particular.

Rehabilitation robotics is a term that describes the use of industrial robotics in medical rehabilitation, and Mechatronics is defined as the integration of electrical, electronics and computing hardware and software technologies with mechanical engineering, forming a strategic approach to the design. Mechatronics involves new theory, experimental procedures and hardware and software development. Of particular interest to many researchers is the use of microprocessors in "intelligent" devices. Furthermore, mechatronics is viewed as encompassing technologies ranging from embedded microprocessor control of intelligent products, to robots and manufacturing automation.

### 1.2.1 Industrial Robot Definitions:

*Industrial Robot:* Description of machines and devices designed both to manipulate and transport parts, tools, implements or specialised devices through variable programmed motions for the performance of a variety of desired tasks [J. Lewis, 91].

*Manipulator:* The term robot and manipulator are often used interchangeably, although this is not correct. A manipulator is defined by the International Standards Organisation as 'a machine, the mechanism of which usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several degrees of freedom. An operator, a programmable electronic controller, or any logic system may control it.' [Manipulating Industrial Robots, 1988].

*Controller:* Controllers perform the necessary arithmetic computations for determining the correct manipulator path, speed and position. However, this information is continuously monitored and fed back to the control system. The robot controller generally performs the following functions: initiate and terminate the motion of the individual components of the manipulator in a desired sequence and at specified points, store position and sequence data in the memory and permit interfacing to the outside world via sensors mounted in the area where the work is being carried out. Generally the controller looks at the error signal and produces some control signal. The controller is often a complicated device which can itself be broken into several blocks.

*Servo-controlled devices:* Servo-controlled devices are subdivided into either continuous-path or point-to-point devices. In either case, each axis loop is closed which permits the manipulator to move and stop within the limits of travel for the individual axes, in addition to controlling the velocity, acceleration, deceleration and jerk for the various axes between the desired stop points.

*Sensors:* Sensors are defined as devices which are able to convert a physical effect into an electrical signal which computers (robots and Mechatronics devices are controlled by computers) can respond to.

### 1.2.2 Previous Work

As part of this research program, a literature review of world rehabilitation robotics research was undertaken to compare existing methods of treatment as well as the study and analysis of any manual or automated machines that are available for treating brain injured patients. The study showed that most rehabilitation robotics projects were investigating workstation systems to help physically handicapped people [Prior, 1990], such systems as the Handy1 robot, the RAID1A workstation and others being used as a means to help the brain injured patient to be somewhat independent. Hardly any effort has been made to design automated or manual patterning machines to help regain natural mobility and/or enhance the mobility of brain injured patients. The investigation has also revealed that most devices available to date, are not used for patterning the whole body of the patient. Instead, they are mainly used as exercising machines for one particular limb of the human body such as the device to exercise the hip extensor muscle. To date the only previous works that attempted to pattern brain injured patients include 1) The Physio-therapy Method and Apparatus invented by James Grant of the United States of America in 1973, 2) The Physical Therapy Patterner invented by Jean Ross of Canada in 1981, 3) The Bed for motor re-education of a patient invented by Pierangelo Magnoni of Italy in 1985 and 4) The Physical Therapy Machine invented by David Sweeny of the United States of America in 1992. However, it is not clear whether these inventions/designs were actually built. A brief overview of the available designs is presented in this chapter. The idea of Dr. Kavina will be fully investigated and appropriate feasibility study regarding design specification, motor selection, control strategies, safety and assembly features will be carried out throughout the course of this thesis. A detailed analysis and discussion of the performance and efficiency of these designs regarding the application of the adopted method of treatment is discussed in Chapter 2.

Briefly, the James Grant invention has provided manipulation of limbs to carry out homolateral and cross pattern movements. It includes a seat, which supports hands

and feet. Cranks are provided with sprockets, which are driven by a drive train. When the machine is to be used for homolateral patterning, the right hand crank and right foot pedal are in phase and the left foot pedal and left hand crank are in the same phase. The phase relationship of the crank can be changed when desired by withdrawing a pin that secures the hand crank [Grant, 1974]. The Jean Ross design, the Physical Therapy Patterner, consists of a table, which is adapted to receive a bench to support the patient in the prone position with four platforms mounted on the table to support the patient's limbs during the creeping exercise. Another four larger platforms are used for carrying out crawling exercises and a head-cradle mounted on the table to support the patient's head through a mechanism comprising of a series of pulleys, shafts, a rocker arm and an aircord [Ross, 1981]. The Pierangelo Magnoni machine consists of a bed and twenty one DC electrical motors to carry out the required tasks. The bed includes a frame which ensures the bed stability during performing the tasks, a platform for transferring the patient from the recovery bed to the machine, a headrest for the patient's head to rest on and arm and foot support leverages when carrying out homolateral and cross patterning movements [Magnoni, 1985]. The David Sweeny design has a horizontal platform with motorised leg, arm and head support, which can be moved separately and selectively to activate specific exercises [Sweeny, 1992].

### **1.3 HUMAN FACTORS**

Before any detailed design specification can be written for any mechanical or Mechatronics device, a review of the general characteristics of the user population and their environment must be conducted to obtain data in the following areas:-

- Human factors information
- Ergonomic data on the availability of machines that are used to pattern brain injured children
- Statistical data on automated devices pertaining primarily to brain injured children.

### 1.3.1 Human Factors Information

Human factors engineering is the practice of designing products so that the user can operate and use the product or perform the required tasks, with a minimum of stress (the human body movements should be kept well within the limits of comfort) and a maximum of efficiency. This research has taken into consideration the steps to stimulate the brain of the injured patient through the physical movements of the following human parts, arms, feet, torso and head along the range of motion at the joints of the body. These movements are given the term "patterning", which is used to describe a series of physical movements carried out regularly on patients, by teams of three to five people depending on the size of the patient. There are several different movement patterns, and each is aimed at stimulating a different brain area, in order to encourage different levels of co-ordinated movement. Each specific patterning technique depends on the needs of the individual patient, and is a primary tool in teaching the nervous system a particular function when this has not yet developed or has been by-passed. These patterning techniques include roll patterning, which requires one person to carry it out by rolling the patient over from side to side slowly and gently. Roll patterning resembles the early movement a child may have experienced in the womb, which helps the child develop an awareness of his body and limbs [Pennock, 91]. Trunkal patterning is a technique that requires two people working in co-ordination with one another to move the child's arms and legs in such a way to recapitulate some of the pre-birth activities of a baby, i.e. the first attempts by the brain to co-ordinate activity in arms and legs simultaneously. The other five patterning techniques:- homolateral creep and crawl, cross pattern creep and crawl and walking, are the main objective of this research project. The latter five techniques require a detailed study of aspects of biomechanics, including strength and speed of human movements as well as the response to such physical forces as acceleration and vibration. The implications of transferring the co-ordinated movements through the sensory parts to the nervous system will be discussed in Chapter 3. Briefly, if a child has sufficient movement in his limbs, but cannot creep forwards on his tummy, homolateral patterning is used to teach the child how it feels to do so. Once the child is able to move forwards unaided, a cross pattern movement can be initiated. This cross pattern movement represents a more sophisticated form of prone patterning,

where, instead of moving one whole side of the patient body at a time, the device/helpers move opposite arms and legs in synchronisation with the patient's head. All patterning is passive in nature, the patient is not required to do anything, at least during the input session where the patient's brain will be fed with information through physical patterning. The purpose of the whole exercise is, in principle, to transmit a series of information to the areas of the central nervous system responsible for the motor functions of the voluntary movements. These co-ordinated movement patterns are to replace the distorted movements the patient has previously had, when attempting to move if the patient possessed any significant movement at all.

### 1.3.2 Ergonomic Data

The proposed idea [Kavina, 96] of developing a novel Mechatronics device to treat brain injured patients has formed the platform of this research work. However, information on the range and sizes of mechanised systems that deal with brain injured patients and data on the home environment are essential when designing such devices to be used at home. Due to the lack of detailed data on design specifications and dimensions, major measurements and studies of the available data of dynamic human body dimensions were undertaken. A study by the author conducted in 1995, revealed that designs available to date do not set detailed specifications and dimensions for designing such an automated machine to carry out patterning techniques for brain injured patients.

On the other hand, researchers have looked into the possibility of using mechanical structures and dampers to limit the unintended movements of the patients and to guide them to move in a desired direction [Downing, 90], as well as the use of some electromechanical devices to test reflex function. Hammond [1956-61] applied mechanical stimuli by means of a constantly rotating wheel, which was clutched in to deliver a stretch through a cable to the arm of the subject. Hagbarth [1967], however applied an abrupt stretch to the limb of the human subject which involved the use of a weight suspended by an electromagnet. When the electromagnet is de-energised, the weight is released, with the resultant fall of the weight applying stretch to the human's limb. Another approach to the application is the use of controlled mechanical

stimuli, utilising hydraulics. This has been developed to a high degree in a number of laboratories, prominent among these laboratories are those of Melvill-Jones, Outerbridge and Young [Humphrey, 91].

### **1.3.3 Anthropometric Data**

Before the design criteria for any mechanised system can be determined, it is essential to establish the dimensional characteristics of the system. There has never been a specific anthropometric survey of such an automated system [Kavina, 96]. The only data available pertains to a survey made by the UK patent office about one mechanical design in Canada and another three designs, supposedly to be used for exercising brain injured patients. The difficulty in obtaining reliable data on this particular group of patients is further hampered by their lack of homogeneity due to the varying range of the severity of the injury as well as the different sizes of patients. Therefore, it is important to take precise measurements of the human body, since the body and reach characteristics of people have a direct influence on such a design. One goal of this research is to enable the patients to be patterned with ease and comfort without compromising the system integrity.

### **1.3.4 Statistical data**

Statistical data on automated devices used by brain injured children are limited. However there are devices available that are used specifically for patterning a particular limb of the human body [Howell, et. al., 93]. In an informal interview with the former director of the British Institute for Brain Injured Children, Mr. J. K. Pennock (currently the director of Brain-Net) revealed that BIBIC has searched and is still searching for a mechanised device to help carry out the patterning techniques of brain injured children. Statistics showed that approximately two million of the world population new born babies are born brain injured, where 18,000 children are born brain injured annually in the United Kingdom alone, [Ferriman, 94]. In the USA alone, an estimated 300 infants and 500 pre-school age children acquire the cerebral palsy condition annually [United cerebral palsy association, 89] and that 56,000 Americans die each year of brain injury [Rehab, 97].



In view of these findings there would appear to be a market for a Mechatronics device, if it were designed to fulfil the patients needs at a cost many can afford. It is estimated that it would cost the United Kingdom government more than £20,000 annually to care for a brain injured child at a special school and an estimated £2.7 million pounds is the life treatment cost for a person with brain injury [Rehab, 97]. Therefore, devices costing up to £10,000 can be considered as low cost, compared with the figures mentioned before, and are likely to be purchased outright privately. However, devices costing over £10,000 and up to £20,000, are more likely to be purchased by local health authorities or by specialised institutes such as BIBIC, Peto and other leading institutes. An alternative to the outright sale might be in the form of leasing arrangement whereby, users hire the equipment for as long as they require it.

#### **1.4 AIMS & OBJECTIVES OF THE WORK**

The aim of this research program is to investigate and conduct a feasibility study regarding design specification, motor selection, control strategies, safety and mechanical kinematic arrangements that will fulfil all design aspects of this novel idea [Kavina, 96]. To perform the tasks of patterning brain injured children to restore, maintain or enhance their natural mobility with the following objectives:-

1. To research the human factors, ergonomics, anthropometric and statistics relating to disabled people, with special reference to brain injured children.
2. To review past and present work in the area of rehabilitation robotics, with special reference to brain injured patients and analyse the approach taken by other groups and determine the best methodology and criteria for the current research.
3. To investigate and evaluate the most important tasks, as defined by BIBIC, to form the most feasible tasks using a suitable criteria based method.
4. To provide a design specification which combines information from the users, together with data from the priority task list set out by BIBIC.

5. To derive a theoretical analysis of the system which describes the performance of the system under different operating conditions.
6. To simulate the full model of the patterning machine, where each unit is driven by a rotary actuator to determine its operational limits and identify the key parameters that contribute to its performance under closed loop control.
7. To investigate novel kinematic arrangements of the arms, feet, head and torso structure in relation to brain injured patients and the type of tasks to be accomplished.
8. To develop a safety control system that ensures safety to both operators and users.
9. To develop a safety critical control procedures and software for the Mechatronics system.
10. To investigate the interactions between force limits and the operator inputs with no compromise to system integrity.
11. To analyse the functional performance of the mechanised device in respect to dynamic and kinematic adaptability of the controller software and ease of use.
12. To provide a working single-axis of the Patterner Machine.

## **1.5 PREVIEW OF THE THESIS**

Chapter 2 consists of a detailed discussion and a world review of the work done in the area of rehabilitation robotics and mechatronics, related specifically to brain injured patients and disabled people in general. It also assesses and exposes the limitations of the manual method currently being used by the most prominent organisations for treating brain injured patients. Points and recommendations are given to help overcome the existing problems with the manual method. The most popular methods

of treatment and their effectiveness are compared. A critical review, discussion and analysis of the available patterning machines is also presented.

Chapter 3 describes human movement as a complex procedure. It states that normal human movements are often automatic in nature and only come under volitional control when circumstances change, e.g. through brain injury, or as a consequence of new experiences. It also states that co-ordinated patterns of movements are presented on a background of normal sensory information and feedback, normal tone, reciprocal inversion, normal balance and reactions. The control of human movement is the responsibility of the central nervous system (CNS) which has the circuitry necessary for learning and re-learning sophisticated movements.

In Chapter 4, an investigation into user requirements and needs is conducted. Questionnaire surveys are presented of dynamic human body measurements which helped in determining the required design and also helped in establishing links between the most important tasks, as defined by the British Institute for Brain Injured Children (BIBIC), and the input from the parents of brain injured children. An overview and a detailed discussion are presented of alternative designs and also why these design has helped formulate to the final design 'Patterning Machine' as proposed by Dr. Y. B. Kavina. Measurements, results and analysis of the dynamic human movements using High Speed Video Cameras are included. The development of mathematical expressions of body joints, such as the movement of the upper and lower arms and the upper and lower legs, as well as the movement of the head. Force interactions between the system and the patient are considered in detail. Explanations of alternative designs and their method of operations are presented. Mathematical expressions are developed to shed light on the understanding of the basic principles of the biomechanic of the limbs concerned with patterning, and to help set-up the final kinematic arrangement.

Chapter 5. looks into the kinematic design of the prototype and presents a breakdown of the steps towards building the mechanical and electrical design. References are made to British and International Standards and details of safety features which should be embodied in the design of the rehabilitation Mechatronics device. It also describes.

in detail, the design specifications for the final product which include the requirement for direct control and a list of regulations concerning safety features, position control and monitoring.

Chapter 6 includes a theoretical analysis of the system is along with relevant calculations and initial harness design. It also contains the simulation results of force interactions between the patients and the machine and a breakdown of the system transfer function. Further more, it presents a review of the conventional electrical rotary actuators and a detailed look into motor control methods.

Chapter 7 considers some system control strategies of the built system. A computer model of the system is created and simulated with good results using ADAMS simulation package and 3D Working Model. Methods of measuring the actual forces exerted by the subjects and results from the simulated and actual operational performance of all the units making up the system under a series of control algorithms are discussed. The algorithm and the subroutines of the software program are presented and explained in detail. Detailed presentations of the system configuration and of the safety mechanisms that were designed and implemented in the system are made.

Finally Chapter 8 contains the conclusions of this research project, and is followed by suggestions given for a range of improvements which could be made to the Patterner Machine with alternative proposed methods to improve safety.

# Chapter 2

## REHABILITATION

## MECHATRONICS RESEARCH

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*'My observation of watching what has happened in rehabilitation, along with other robot activities, is that it has been heavily repetitive. Certainly not without exception, but it seems to rise to the same level of incompetence.'* (Joseph F. Engelberger)

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### 2.1 INTRODUCTION

Rehabilitation robotics covers a very wide area of research, encompassing fixed and mobile robots as well as prosthetics, orthotics and control engineering amongst others. However, there is very little mechatronics research into the area of brain injury rehabilitation. The diversity of this type research meant that very little detailed information pertaining to the number of researchers or the type of research in this certain area existed. The need for such information has prompted the author to conduct a detailed review of world research in rehabilitation mechatronics and robotics.

A detailed review of world rehabilitation mechatronics research was undertaken as part of this research programme. This chapter presents the results of the world review together with a detailed analysis of patterning devices available to date. Physical measurements of the human body relating to brain injured patients, especially brain injured children were undertaken. These measurements were taken mostly in the prone position. These measurements played a big role in determining the sizes and lengths of the units. The criterion used is that the final kinematic arrangement must be suitable for at least 95 % of patients.

## 2.2 REVIEW OF REHABILITATION MECHATRONICS RESEARCH

The objective of this review was to establish the number of research centres active in the rehabilitation area of patterning brain injured patients and to analyse the machines available that closely deal with the physical movements of the patient. The Doman-Delacato method or simply the bench method, and the Conductive Education method were carefully studied. To the author's knowledge, there have not been any such reviews of rehabilitation mechatronics in the past. The review was conducted by collecting any paper, newspaper, journal article, patent or conference proceeding relating to rehabilitation mechatronics and robotics from all over the world.

### 2.2.1 Discussion of the World Review

The review showed that there were few projects that deal with brain injured patients. Many of these rehabilitation robotics projects investigated workstation systems [Prior, 90]. The reasons for this are, generally speaking, problems of cost, space and public awareness.

Over the past 20 years, there have been many attempts to develop robotics devices with the aim of improving the lives of disabled people by acting as aids to living rather than having the objective to help them restore or enhance their natural skills. In the USA, Larry Leifer designed a robotics workstation, De VAR (Desktop Vocational Assistant Robot) at an estimated cost of £50,000. In Holland, Kwee designed the MANUS teletheses, a demountable wheelchair robotics manipulator system at an estimated cost of £30,000. The Handy 1, is the most commercially successful system in the world, at an estimated cost of about £4,000 [Topping, 95]. The investigation has also revealed that most devices available to date are not used for patterning the body as a unit but rather exercising one particular limb. i.e. the hip extensor device [Howell, 93]. Designs that have been proposed for patterning brain injured patients, include the physiotherapy method and apparatus invented by James Grant of the United States of America in 1973, the Physical Therapy Patterner invented by Jean Ross of Canada in 1981, the Bed for Motor Re-Education of patients invented by

Pierangelo Magnoni of Italy in 1985 and the Physical Therapy Machine invented by David Sweeny of the United States of America in 1992. It is not clear whether these designs were actually built.

### ***2.2.1.1 The Handy 1 Robot***

The Handy 1 Robot was originally developed to meet the needs of a 12 year old boy with cerebral palsy who wanted independence at mealtimes. The model was based around the 1988 existing technology of a Cyber 310 robot with five degrees of freedom and a gripper. Then Handy 1 was improved with the ultimate aim of producing a multi-functional system capable of helping a large number of different disability groups to include, cerebral palsy patients of ages 4 to 57 years, stroke patients aged 45 to 61, accident patients aged 21 to 49, muscular dystrophy, male, aged 7 to 17 years, elderly aged 62 to 88 years and motor neurone, female, aged 39 to 46 years [Topping, 95].

At present there are no rehabilitation mechatronics or robotics systems dealing with patterning brain injured patients available to the general public. The present treatment is largely manual including the Conductive Education method and the Doman-Delacato method often referred to as the bench method. The bench method which what this research is based on was developed by Doman et. al. and was formalised in 1961. The bench method requires the patient to be placed in the prone position and being patterned by three to five helpers depending on the size of the patient. The patterning is carried out for a specified duration of time every day for weeks, months or even years. i.e., frequency, intensity and duration, until the patient improves.

### ***2.2.1.2 The RAID 1A Workstation***

The Robot for Assisting the Integration of the Disabled (RAID) workstation is designed around a modified OxIM RT200 robot with linear rail, extended vertical reach and OxIM tool-changer. It is designed to allow the user to be independent for at least four hours at a time, with respect to the following tasks: fetching and returning a

book, opening and closing a book, page turning back and forth, taking papers from printer, stapling documents, handling telephone calls, moving disks and CDs from racks to the PC and back again and presenting the user with a drink [Jones, 95].

The Handy 1 system and the RAID workstation can be used to help people with special needs, by enabling them their chances of integration into a normal environment. But they cannot help the patients recover from their illness and will not help them restore or enhance their natural mobility, because there is no appropriate stimulation to their brains.

### **2.3 CRITICAL REVIEW OF PATTERNING PROJECTS**

Researchers have looked at the use of electromechanical structures and dampers to limit the unintended movements of brain injured patients [Downing, 1990]. Most of these electromechanical devices are used to test reflex functions. These devices lack the necessary automation and intelligence to carry out the task of patterning as an input/output exercise.

A literature review of the last forty-two years has discovered only four major projects, however, there is no evidence that any of them has been built. Of these designs; one is a high-cost solution, the Physical Therapy Machine, another is a low-cost solution (not fully automated), the Physical Therapy Patterner, and of the other two, one of them is a proposed development of a bed for Motor Re-Education of a patient and the other does not comply with the bench method which is considered to be essential for brain injured patients to restore or enhance some of their natural mobility.

The project reviews which follow will give the reader a sense of the attempts made by a small group of people who encountered this problem in real life or heard about it from a friend and tried to do something about it. It will also show the lack of contact between members of this small community.



### 2.3.1 The Manual (bench) Method

In every culture, a baby is placed on the floor very early in life. Every baby is encouraged to roll over, creep and crawl and will eventually walk unaided. Child experts have recognised the value of the floor as a natural environment for a child. This is true as far as a healthy baby is concerned. However when it comes to children with brain injury, such children need to receive special or additional sensory stimulation to develop motor learning and control, where motor learning focuses on understanding the way in which the processes that serve movement are developed. The degree of success is determined by how quickly that a brain injured child will respond to stimuli. Patterning will help a brain injured child, with respect to reaction time (time that lapses between the appearance of a signal to move, or the stimulus, and the beginning of a movement) and movement time (the interval of time from the beginning to the end of the movement). This can be termed as input sessions and output sessions, i.e. when the child is being moved in an organised manner such as homolateral creep, the information is stored in the healthy cells of the child's brain. The frequency of these organised movements will help the child perform these movements unaided [Doman, 60].

The bench method as it is known in the UK, or the Doman-Delacato method, for brain injured children resembles the floor for a normal healthy child. Brain injured children not only need to receive special or additional sensory stimulation (input session), they also need an increased opportunity to do things themselves and to learn by repetition the same information as healthy children would normally learn. While lying flat in the prone position, the body does not require any sort of balance. The body is at rest, so no demands are made on muscles to maintain position and the effects of gravity can be largely ignored. The bench method deals with stimulating the areas of the central nervous system, CNS, (discussed in Chapter 3) responsible for motor functions. Figures 2.1 a and b show cross and homolateral pattern creep, cross and homolateral pattern crawl. The bench method is designed to move all the limbs of the injured person in a co-ordinated manner in accordance with the severity of the injury (speed of movement is determined by medical staff). The purpose of these co-ordinated

movements is to stimulate the healthy brain cells to store the new information and then output it when needed.

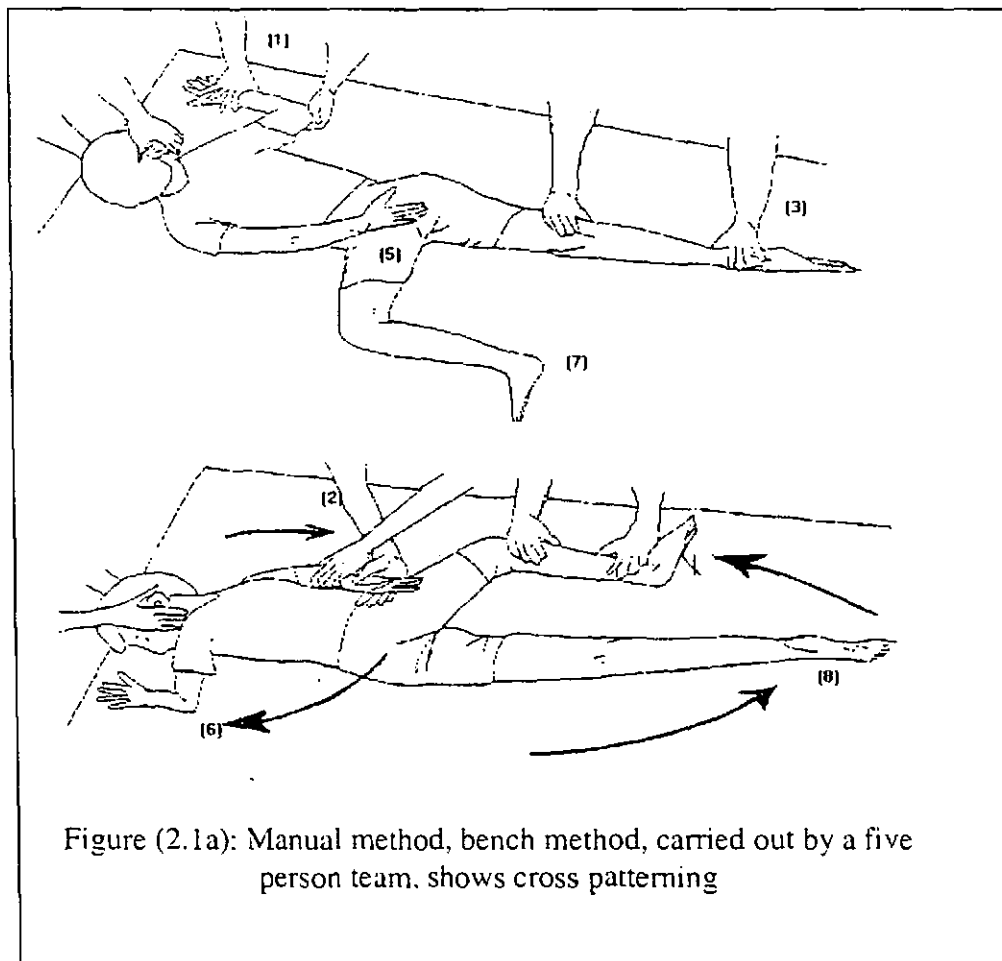


Figure (2.1a): Manual method, bench method, carried out by a five person team. shows cross patterning

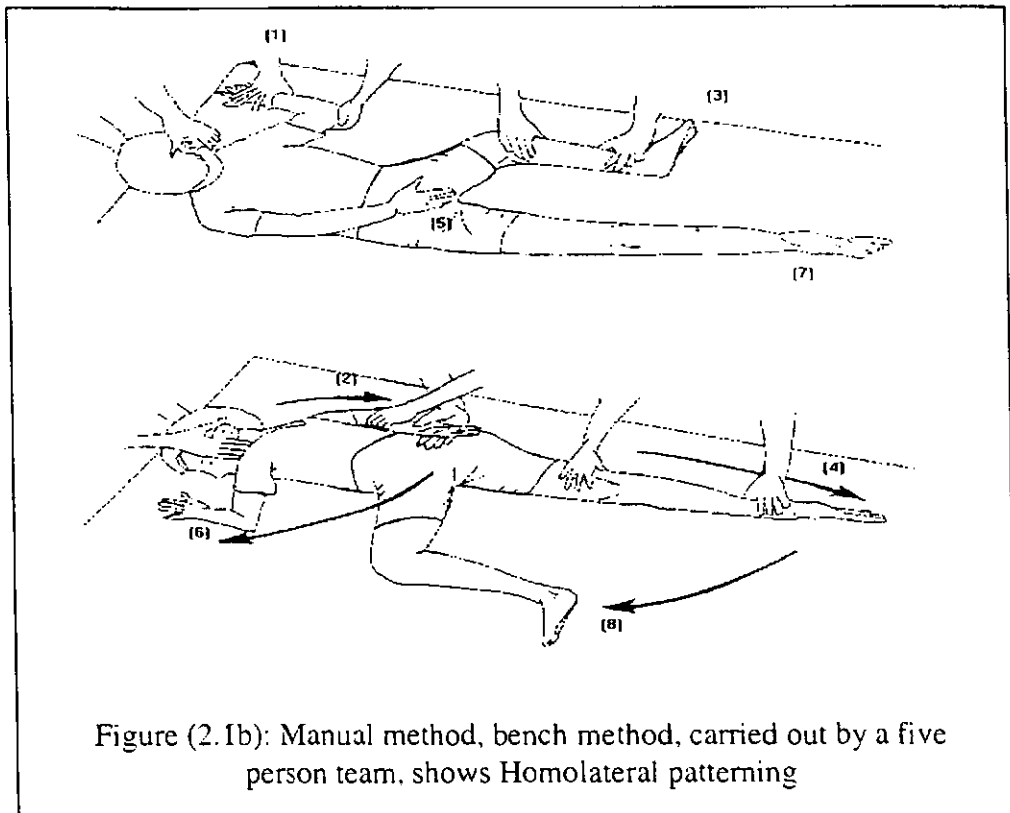


Figure (2.1b): Manual method, bench method, carried out by a five person team, shows Homolateral patterning

### 2.3.1.1 The Doman-Delacato Development Profile

Each brain injured child is individually assessed using specially produced Doman-Delacato developmental profiles (appendix B) which detail the level of development ordinarily reached by a healthy child. This profile gives the child's neurological age (or the age of development at which the brain is functioning) by measuring functions at six basic levels. These functions are mobility, production of sound, manual competence, visual competence, auditory competence and tactile competence.

These basic levels are divided into stages of graded neurological development, i.e. mobility is divided into moving arms and legs but without locomotion; crawling in the prone position or commando style; cross pattern crawling, moving arms and legs on opposite sides; creeping on hands and knees; standing and balancing as listed in Table 2.1. [Pennock, 91]. Programmes for each child are then determined to provide stimulation to the brain through physical activities. The level of treatment is judged by medical experts as the right level in each stage. However, it should be noted that

Doman-Delacato therapy does not stimulate later stages of development until each earlier stage has been successfully achieved, i.e. creeping before crawling and crawling before walking.

#### 2.3.1.1.1 Assessment Program

When the brain injured child is admitted to the clinical institution, a complete and thorough medical check-up is performed and an assessment of the level of activities the child is able to perform is noted. Based on the above, a level is given to that child according to Table 2.1. The visit to the clinic usually lasts for a week where the child under goes a programme constructed by the medical doctors in the institute to carry out the patterning techniques set out by the institute. The parents of the brain injured child are also trained to help them carry out the patterning techniques once the brain injured child is discharged from the clinic.

Table 2.1: Time scale (age) in terms of mobility

Time Frame	Level	Mobility
Peer level (if over 6 years)	8	Able to move with co-ordination of age level, consistent with appropriate foot
6 Years	7	Able to hop, skip, jump and kick a ball
3 Years	6	Able to run in cross pattern
18 Months	5	Able to walk with arms no longer required for balance
12 Months	4	Able to walk with arms used for balance
6 Months	3	Able to crawl in cross pattern on hands & knees
3 Months	2	Able to creep in cross pattern on abdomen
Birth	1	Free voluntary movement of limbs

### ***2.3.1.2 Conductive Education Development***

This technique of conductive education is widely adopted by the Peto Institute where each child attends several sessions during a two week visit to the centre. At the centre all children will be working in small groups supervised by a conductor (a highly trained remedial treatment health care specialist). Due to the nature of conductive education the daily routine will vary between the groups of patients. Each child's daily routine will include several series of tasks carried out in different positions, lying position, sitting position and standing-walking positions. All these positions are not a set of separate programmes, but rather they are inter-linked and to be applied in activities throughout the day. This idea is based on the fact that normal healthy children take part in educational activities as they use skills they have previously learned. The group activities also play a part in building and developing the personalities and social skills of brain injured children. Therefore conductive education is mainly based on the self esteem of the patient by giving the child an achievable goal that with some effort can be achieved. It is therefore, the author's decision to use the Doman-Delacato method (bench method) rather than the conductive education method, because the input aspects of Doman-Delacato method are passive in nature and do not require the brain injured patient to put any considerable efforts during the input session. Note, however that the output session can be at first assisted and later unassisted, thus requiring the patient to put into practice the therapy imposed during the input session.

### ***2.3.1.3 Effectiveness of the Bench Method***

Doman, et. al. studied physical movements of seventy six cerebral palsy children during 1956 and 1957 and developed a new approach to such cases, which came to be known as the bench method. Three conditions were set for the study 1) the existence of brain injury (brain injury was defined as applying to those children whose lesion lies in the brain), 2) a minimum of six months treatment and 3) no child was to be eliminated because of the severity of the disability. The group of children was in the age range of twelve months to nine years old with a median age of 2.2 years and a mean age of 2.5 years. The children were separated into three age groups of

developmental significance: there were 16 children in the age range 0 to 18 months, 41 children in the age range 18 to 36 months and 19 children in the age range of over 36 months. Tables 2.2 and 2.3 list the three classifications (type, location and degree) of the 76 children after the diagnosis of the Brain Pathology [Doman, 60].

Table 2.2: Classifications of the type of deformity

Type	No. of children	Remarks
Unilateral brain damage	15	All operated on
Bilateral brain damage	61	All operated on

Table 2.3: Classification of the location of deformity

Location	No. of children	Remarks
Lateral ventricles	30	Demonstrated dilatation
Entire ventricular	12	Presence of subcortical and cortical damage
Midbrain lesions	12	Athetoid patients
Basal ganglion lesions	3	2 with tremor and 1 with rigidity
Cerebellar lesions	10	Ataxic patients
Spastic patients	61	Phelps-Fay classifications

As for the degree of brain damage classification, all brain injured children under study were in the range of mild to severe. No child was eliminated from the study due to severity of either clinical symptoms or degree of brain pathology.

#### *2.3.1.4 Methods of Treatment*

The role of physiotherapy in cerebral palsy is still debated, but there is much evidence that, particularly when started very early, it is effective not only in preventing severe contractures and deformity but also in permitting more normal motor development [Bartlop, 87]. Therefore, the purpose of the study was to determine and evaluate the disability of the children in functional terms. The treatments prescribed to all non-walking children was to spend all day on the floor in the prone position and were

encouraged to crawl (prone method) or creep (hand-knee method) until the level of accomplishment was possible. Then a special pattern of activity was prescribed (homolateral and cross pattern) which was to be passively imposed on the central nervous system of the patient by the parents or helpers. There were 44 children who could not crawl, 7 who crawled below cross pattern level and 5 who could crawl in cross pattern or who could creep [Doman, 60].

### ***2.3.1.5 Results of Treatment***

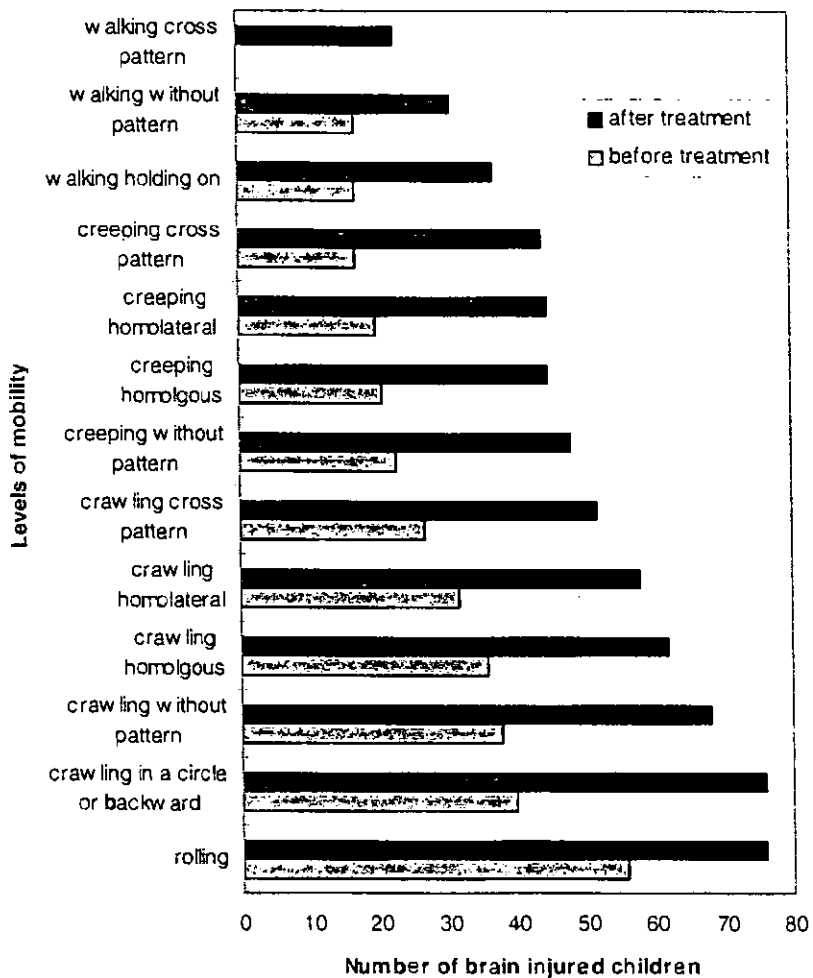
The results showed vast improvements of the patient's physical ability. Of the seventy six children, twelve were ready to walk at the end of the treatment duration, eight children were creeping cross pattern and four other children were holding onto objects. Eight of the group of the children who were able to walk at the start of the study programme improved significantly, but were not considered as having increased their functional competence by one level. All but two children improved by at least one level. Eleven children learned how to walk completely independently (without any means of support). Six out of the 72 children were discharged, all of whom had learned to walk perfectly [Doman et al, 60]. These results as shown on Figure 2.1 below gave clear indication that the central nervous system can be stimulated through physical activities provided that the movements follow an organised pattern with the right intensity, frequency and duration.

### ***2.3.1.6 Discussion and Observations***

Dr. Doman et. al. observed that opportunities for the brain injured child to crawl and creep were rarely agreed, acknowledged or emphasised. Therefore greater emphasis should be placed on letting the brain injured child use the floor, which has been described by Gesell et. al., as the normal child's "athletic field" [Gesell, 47]. The procedure Dr. Doman adopted was based on the premise that certain brain levels, i.e., pons, midbrain and cortex have responsibilities in terms of mobility and the aim was to create a climate in which the brain injured child may develop and utilise those brain cells that are uninjured [Thomas, 52]. The above results obtained by Doman, et. al., shown in Figure 2.2, proved that it is possible to regain limb co-ordination and motor

function control using patterning techniques. The undamaged cells in the central nervous system, CNS, can be reprogrammed to restore or enhance motor control of a brain injured patient by patterning techniques.

Fig: 2.2. Results in terms of mobility

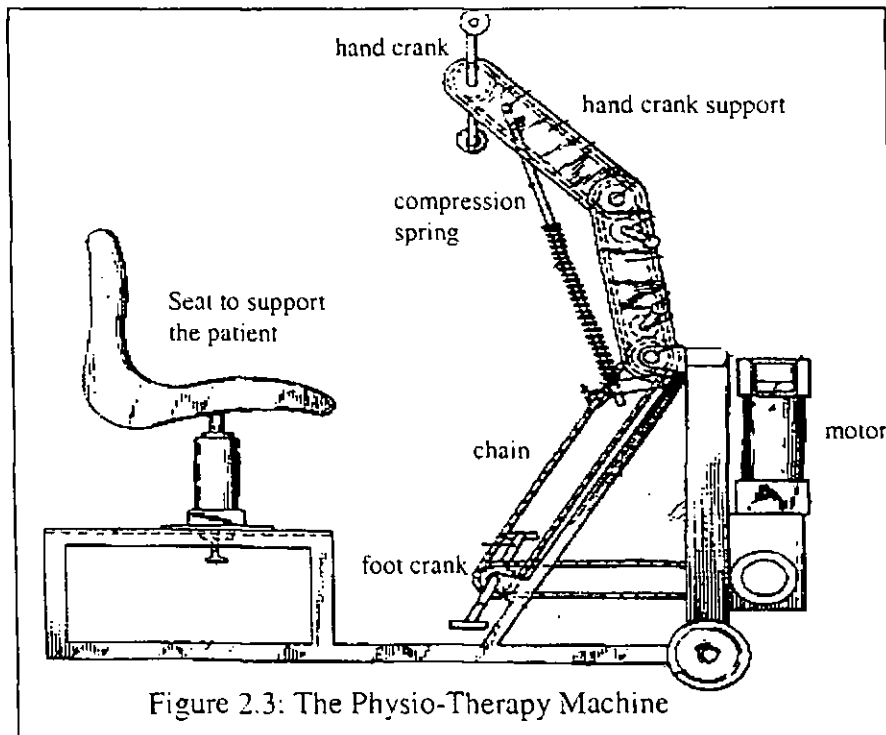


2.3.2 The Physio-Therapy Method and Apparatus, (USA, 1973)

This machine, as shown in Figure 2.3, is used for teaching brain injured children or adults the homolateral patterning techniques and cross patterning techniques. This machine includes commonly driven foot cranks and hand cranks that are adjustable to afford use of the cranks in the proper angular phase for homolateral and cross



patterning therapies. The apparatus includes a motor and a variable speed drive to rotate the cranks and to manipulate the patient's limbs in the proper fashion to teach the desired patterning techniques. There is also a clutch in the drive train to enable free wheeling of the cranks by the muscle power of the patient as learning progresses with use of apparatus in the driven mode. No information regarding variation of speed and power was available [J. Grant, 1973].



### 2.3.3 The Physical Therapy Patterner, (Canada, 1981)

The machine is a power-driven therapeutic machine, as shown in Figure 2.4, designed to replace the three to five helpers needed to impose passive homolateral creeping and crawling therapies and cross pattern creeping and crawling therapies on the brain injured patient. The weight of each patient is borne by the benches and head-cradle of the machine while the limbs and head are moved in rhythm. All of these movements are made for them while they are in the prone position. The machine is comprised of a table to receive a bench to support the patient in a generally prone position. Four reciprocating platforms mounted on the bench and are used to support the patient's limbs while undergoing the creeping techniques. Four larger platforms are adapted to lift over the reciprocating platforms, to support the patients' limbs while undergoing

crawling techniques, and a reciprocating head-cradle, mounted on the bench, and is adapted to support the patient's head through a mechanism comprising a series of pulleys, shafts, a rocker arm and an aircord. Again no information regarding the type of motor, the speed or the power was available [Ross, 1981].

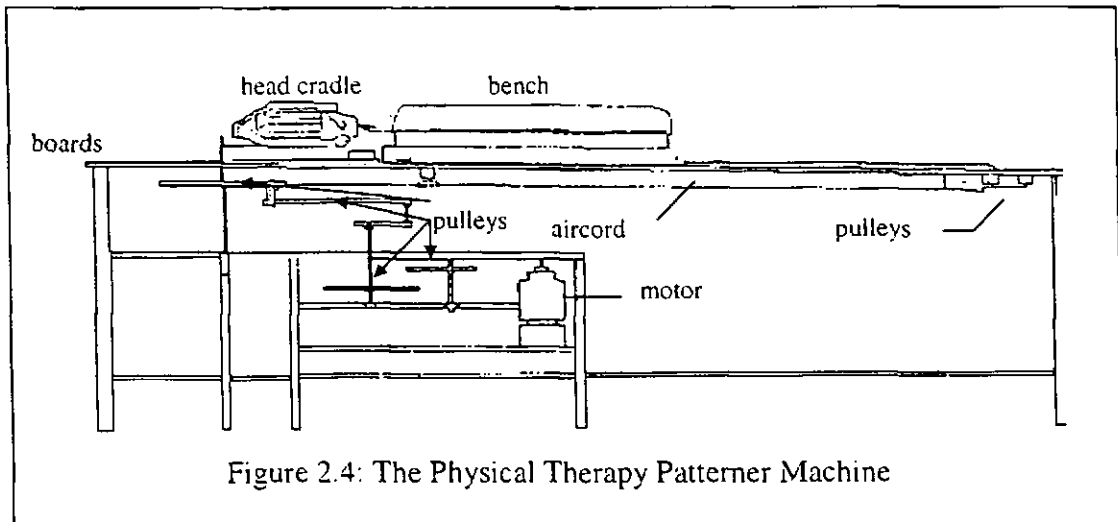
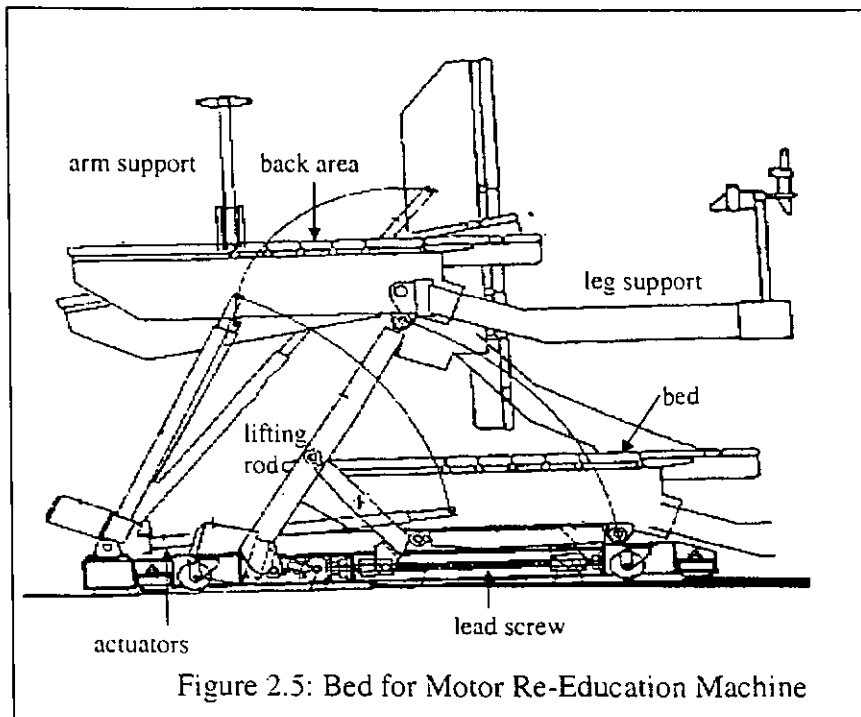


Figure 2.4: The Physical Therapy Patternner Machine

#### 2.3.4 Bed for Motor Re-Education of a Patient, (Italy, 1986)

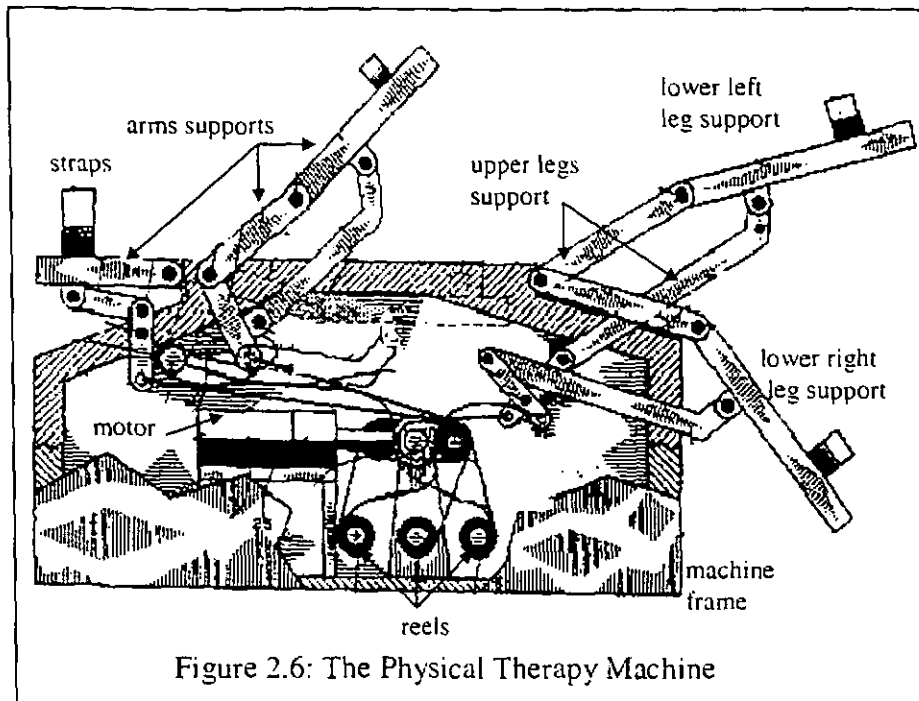
The bed for passive, autopassive or against patient resistance, Motor Re-Education as shown in Figure 2.5, is supplied with twenty-one low voltage DC electric motors. These motors are to control, respectively, eleven mechanical assemblies applied to the bed. Each mechanical assembly is made to cause the different movements of the patient. Two further auxiliary mechanical assemblies constrained to the former and at least another eight for the positioning and the necessary adjustments of the bed. The bed therefore, can be adjusted to the desired height and it revolves around a transversal axis.

The operation of the motors is servo controlled. A speedometer and the torque via torque detectors control the speed. The machine is operated by a microprocessor to guarantee soft, constant, stable and repetitive movements of the task required. It is also provided with a video which allows the operator to visualise the stated data such as sequence, intensity, amplitude, duration, execution, speed, acceleration and stall torque value [Magnoni, 1986].



### 2.3.5 The Physical Therapy Machine, (USA, 1992)

The physical therapy machine in Figure 2.6 has a horizontal body platform on a machine frame with motorised leg, arm and head support members that are moveable separately and selectively to activate body joints associated with major muscle groups of the disabled individuals and brain damaged children. Cables connected to reels, are positioned in contact with pulley wheels on eccentric cranks. These cranks are rotated to transmit oscillational travel of total limb-support members and of section of the limb-support members circumferentially through a lever for each limb. The angular degree of circumferential travel of separate body-limbs supports is adjusted by varying the length of the cable via eccentric cranks. Circumferential hinge restrains are used to adjust the angular oscillational travel sections of the separate body-limb supports. Muscle-resistance is provided progressively and simultaneously with joint activation, by resistance to oscillational travel of the limb-support for brain damaged patients [Sweeny, 1992].



## 2.4 EVALUATION OF CURRENT PATTERNING DESIGNS

### 2.4.1 The Physio-Therapy Method and Apparatus

The method and apparatus of this design provide manipulation of the limbs in order to teach the homolateral and cross pattern techniques. The frame includes a seat, and also supports hand and foot crank. Although the cranks are provided with sprockets, which are commonly driven by a variable speed motor, the position in which the apparatus is situated requires the patient to put some effort into performing the desired patterning techniques tasks. The apparatus includes a removable guard for the drive train and sprockets. It also provides either a free wheeling mode or a motor driven mode.

The Physio-Therapy Machine does not comply with the bench method, and does not give any support to the patient in the free wheeling mode, as well as not mimicking the actual movements (actual creep and crawl) of a healthy child. It is vitally important for a brain damaged child who has never crept or crawled to be stimulated by natural development and to follow the progression of a normal healthy child. A

platform should act like a floor from which to carry out the desired essential patterning techniques. However, this apparatus does not provide such essential patterning, but it provides only “on the spot” movements. It is neither computer operated nor computer controlled. This design seems to be more suitable for persons who have suffered sports related injuries, than for those who are suffering from brain damage.

#### **2.4.2 The Physical Therapy Patterner**

A motor operates this power-driven therapeutic machine, by means of V belts and a set of pulleys. At a fixed speed the supporting arms get turned through a complete circle, as the arms turn, the platforms move in a back and forth motion. Although this apparatus follows the bench method very closely, it cannot perform all the patterning techniques without the help of two additional wider platforms. This Patterner is very heavy, not robust, and needs more than one person to change the platforms. One further major drawback that it is not programmable and not computer controlled. Force interactions and patient resistances do not appear to have been considered. Safety is not stressed fully, i.e. no mechanical or electrical stops were implemented. It does not protect the user against excessive torque. Above all it provides “on the spot” movements only.

#### **2.4.3 The Bed for Motor Re-Education of Patients**

Although this machine is microprocessor controlled, it lacks one of the most important features which is to be able to mimic the natural development and progression of a child who is not disabled. Furthermore, it is very expensive to build (twenty one motors plus drives and controllers), provides “on the spot” movements only, and cannot be used in the home environment due to its heavy weight (21 motors) as well as its complexity which makes it difficult for an ordinary person to operate.

#### 2.4.4 The Physical Therapy Machine

This machine has a horizontal body platform equipped with motorised leg, arm and head support members. Each of those members can be moved separately and selectively to move any desired limb. Although this machine does not follow the bench method it does move the whole body of the patients. The physical therapy machine seems to be based on existing exercising machines. Its major drawbacks are; it does not allow the patient to be placed in the prone position even though the prone position is the natural way for a child to develop movements, and it only provides “on the spot” movements. This machine is more suitable for disabled persons such as paraplegics and arthritics who need the help of physical therapists and others under the direction of medical doctors, to manipulate and to work the joints of their bodies.

#### 2.4.5 Review Summary

The discussed patterning machines do to some extent perform the required tasks of homolateral creeping and crawling and cross pattern creeping and crawling. However none of these were designed to perform walking although it is natural for a child to walk after having learned how to creep and crawl. Two of the four designs do not fulfil the requirements of patterning by not including the use of the floor, although it is an essential part in the development of motor learning. These designs provided no specific physical measurements pertaining to brain injured patients (especially in the prone position). therefore it was necessary to undertake full scale surveys among healthy and brain injured children to set out the outlines for an optimum kinematics arrangement for the proposed Patterner Machine (presented in Chapter 5).

Table 2.4: Comparison of the existing patterning machines

Able to Perform:	Physio-Therapy Method	Physical therapy Patterner	Bed for Motor Re-Education	Physical Therapy Machine	The Ideal Mechatronic device
Basic Tasks	yes	yes	yes	yes	yes
Natural Patterning	no	no	no	no	yes
Creep on abdomen	no	no	no	no	yes
Crawl on Hands and Knees	no	no	no	no	yes
Walk with arms used for balance	no	no	no	no	yes
Free voluntary movement of limbs	no	no	no	no	yes
Aided output sessions	yes	yes	yes	yes	yes
Used at home	yes	yes	no	yes	yes
Assembling	difficult	difficult	difficult	difficult	easy
Estimated Initial Cost	moderate	moderate to high	very High	very High	high
Position Accuracy	low to moderate	low	moderate to high	high	high
Speed	N/A	fixed	variable	fixed	Variable
Flexibility	low	low	moderate	moderate	high
Transportation	difficult	moderate	difficult	moderate	easy
Safety	average	average	high	average	high

Since brain injury often occurs at early ages, the above machines did not demonstrate that a 6 months old baby could use them effectively. Also these machines do not accommodate the wide range of patient sizes nor they specified the ages of patients who might benefit from these machines.

#### 2.4.6 Lessons Drawn from Previous Work

From the above review of rehabilitation robotics and patterning devices, several important points were noted for the design and implementation phase of the present research project. There are many reasons why projects of this type fail to reach a production stage. Some of these will be financial and some will be through specific design decisions made along the way. The following list highlights lessons drawn from the review of previous work such lessons being fully noted for this research project.

- Multidisciplinary teams, involving mechanical and electronic engineers, electrical product designers, brain damaged patients, medical advisers, psychologists and marketing, sales and support specialists, must be consulted throughout the relevant phase of the project.
- There must be an ability to pattern the whole body.
- Cost to users must be reasonable.
- The scope of the design specification must be focused upon the most fundamental and most important requirements of patients needs, and nothing else, (reduced labour and increased efficiency).
- system integrity must never be compromised.
- The system must be very safe and as simple as possible.
- The system must enable the patients and operators to perform the desired tasks efficiently and to relieve the user of unnecessary time delay, frustration and fatigue.
- A programmable microprocessor based control system and a multimedia system are strongly recommended.

## 2.5 SUMMARY

Different examples of prior art can be found in numerous exercise machines. Regardless of their structure, previous devices discussed above are designed to resist the natural action of the muscles rather than help aid the muscles and related body joints. The aid for assistance in movement of the joints has not been addressed fully in the pervious inventions. Instead, the needs for joint exercise separately from muscle exercise have been supplied in the previously reviewed machines. They



manipulate body joints manually. The review has shown that the Doman-Delacato method is an effective way of providing brain injured patients with suitable stimuli over a period of time.

The review has shown that there is very limited ongoing activity in rehabilitation robotics and mechatronics in the area of brain injury. It has highlighted the different but positive attitudes towards the design of a fully automated device for the sole use of brain injured children. Even though, there has not been a vast amount of money, there have been many man-years of effort spent in finding the ideal system for patterning brain injured patients. The idea of general purpose rehabilitation robotics and mechatronics, which can be used for a large number of patients with brain injury, and which can be readily available at low cost is still some way off.

Analysis of the projects available to date showed that even in this narrow field of research there is one central theme within all these projects, which is to help brain injured patients to restore or enhance their natural mobility and become more self sufficient and independent, where their self esteem will increase and their social value will be truly realised.

Finally, the proposal of Kavina, 96 will form the main starting point of this research project and will be discussed in details.

# Chapter 3

## HUMAN NERVOUS SYSTEM AND MOVEMENTS

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*'In a person who is open to experience, each stimulus is freely relayed through the nervous system, without being distorted by any process of defensiveness.'* Carl Rogers

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### 3.1 INTRODUCTION

The nervous system provides most of the control functions of the body. The nervous system is unique in performing the control actions. It receives thousands of bits of information per second from different sensory organs and integrates all these to determine the response to be made by the body. Input by the nervous system is provided by the sensory receptors that detect sensory stimuli such as touch, sound, light, cold, heat and so forth. The purpose of this chapter is to discuss the input signals and the basic mechanisms by which the receptors change sensory stimuli into nerve signals and also to establish a link between the input signals to the brain and the output signals produced by the brain after a period of time.

### 3.2 THE CENTRAL NERVOUS SYSTEM: AN OVERVIEW

It is essential to give an overview of the brain and its functions before discussing the control of movements. The brain is enclosed in a double membrane, with a fluid forming a water cushion enclosed by the membrane, and is protected by the bony walls of the cranium. The central nervous system is connected by pairs of nerves to various organs in the body. Its functions are primarily to receive information as to what is arriving from inside various parts of the body and also from outside, and to

use this information to enable the person to react suitably in order to control the activities of the body, and to make all parts work together for the benefit of the whole body (co-ordination). Moreover, the brain of a human being consists of two separate halves, or hemispheres. There is a cross-over network which links each hemisphere to the opposite side of the person, so that the right hemisphere takes part in controlling some activities of the left side of the body and vice versa [Mason, 1980]

### 3.2.1 Function of Various Parts of the Brain

There are regions in the cerebral hemispheres, which are separately associated with sight, hearing, taste and other sensations. The cerebrum functions as the organ of the mind connected with emotions, thought, reasoning, memory and consciousness, while the voluntary movements are produced by nervous impulses, which originate in the region of the brain (side view) shown in Figure 3.1, below. The cerebellum is concerned with the maintenance of the balance and co-ordination

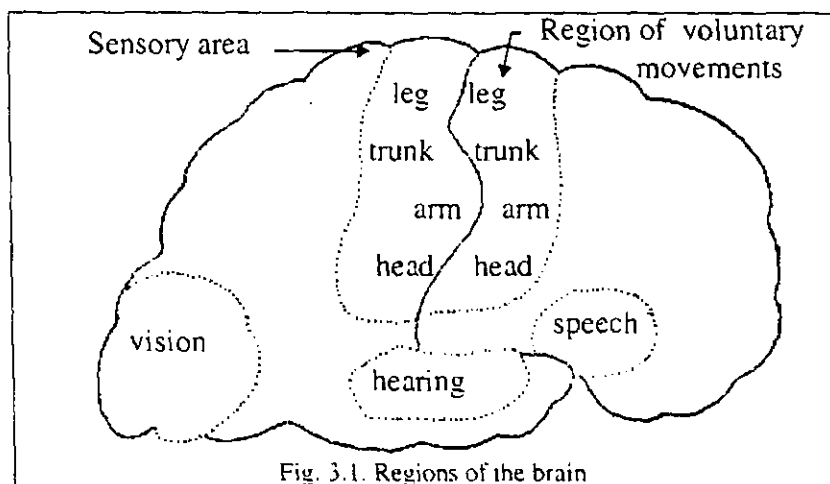


Fig. 3.1. Regions of the brain

of muscular movement, i.e., when a foot is bent, nervous impulses from the cerebrum first pass to the cerebellum for sorting out and transmission to the requisite muscles. With practice many voluntary actions such as those to be taught by patterning techniques can be made automatic by training the cerebellum to co-ordinate the necessary muscles. Note however that in early life, the muscular movements are much less co-ordinated before the cerebellum has become fully trained [Barker, 69]. The medulla (the remaining part of the brain) which is responsible for individual

movements of the arms and legs, is concerned with regulating automatic actions and uses the spinal cord as the pathway for nervous impulses passing to and from the limbs, the trunk and the brain.

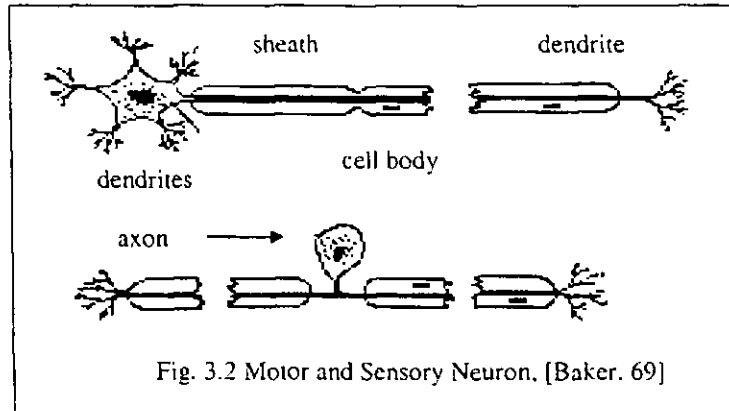
### 3.2.2 How the Nervous System Operates

The nervous system has three major levels that have special functional significance:

- 1) the spinal cord level where the sensory signals are transmitted. These signals can cause localised motor responses either in the segment of the body from which the sensory information is received or in adjacent segments. All spinal cord motor responses are instantaneous in response to the sensory signals.
- 2) the lower brain level which is responsible for the subconscious activities such as control of arterial blood pressure of the body.
- 3) the higher brain level or cortical level, whose main function is primarily to store information, i.e. where most of the memories of past experience and also many of the patterns of motor response are stored.

The nervous system is therefore made up largely of nerve cells called neurons (cells that receive and send information through out the nervous system). These neurons, in the range of 100 to 200 billion, are the largest cells in the body. A small neuron may measure about 3 micrometers but the largest one may stretch for over a metre and far more depending on the size of the person. Each neuron has one or more branching processes called Dendrites (a branching process of a nerve cell by which nervous impulses enter the nerve cell) and one long process called Axon (a long process of a nerve cell along which nervous impulses leave the nerve cell). Neurons with their axons and dendrites interconnecting the cells, result in a formidably complex arrangement [Hoyenga, 1988]. The function of the neuron is to transmit nervous impulses or to originate them for transmission. The impulses always enter via the axon and leave via the dendrites. In order for the nervous impulses to pass from one neuron to another as shown in Figure 3.2, the terminal dendrite of its axon interlaces

with a dendrite of another so that the impulse may jump the small gaps called synapses (the gap between the terminal dendrite of one nerve cell and the dendrite of another) between them.



The central nervous system is linked to a large number of neurons which form what is known as reflex arcs. The simplest type of reflex arc is found in the spinal cord, and is known as a spinal reflex. It consists of three linked neurons:

- 1) the receptor or sensory neuron which receives a stimulus.
- 2) the relaying or connector neuron which connects a sensory neuron to a motor neuron.
- 3) the motor effector neuron which transmits nervous impulses to the effector organ (muscle or gland) which makes a response.

A baby learns to sit up when organs of balance in the internal ear have established reflexes with the motor neurons working the muscles of the limbs and trunk. The basic reflex for standing, crawling, sitting, walking and running depend on built-in circuits of neurons in the spinal cord, connected to circuits in the centre of the cerebral hemisphere muscles and about all other inputs to the central nervous system.

Most movements are programmed by the brain, and they use lower-level reflex arrangements as their components, i.e. when a computer key board is touched, the

impulses leave the brain, programmed in time and place to hit the keys in order. Therefore when a stimulus such as patterning is applied to the body, a series of nervous impulses is started in the dendrite of a sensory neuron. These impulses travel in the sensory neuron to the grey matter (a central region surrounding the central cavity) of the spinal cord. Here they are passed on through a relaying neuron to a motor neuron, whose axon conveys them to a muscle fibre [Gregory, 87]. Response to the desired action depends on the frequency, intensity and duration of the stimuli.

### **3.3 CONTROL OF HUMAN MOVEMENTS**

The most important function of the nervous system is the control of the bodily activities internally and externally, e.g., motor functions, whether that be the activities within the body itself such as the movements of internal organs or the normal recognisable movements of the limbs. Human movement follows a unique natural pattern where most of the movements are automatic (once they have learned). These patterned natural movements are subject to new experiences. Most healthy humans have well balanced patterns of movements. These co-ordinated movements are learned in the early stages of the development of the human through normal sensory information and feedback [Todd, 1986].

#### **3.3.1 The Motor Division**

The nervous system control of the body is achieved by controlling:

- a) contraction of skeletal muscles throughout the body.
- b) contraction of smooth muscle in the internal organs.
- c) secretion of both exocrine and endocrine glands in many parts of the body.

These activities are called motor functions, and the muscles and glands are called effectors because they perform the functions dictated by the nerve signals. The motor division of the nervous system is directly concerned with transmitting signals to the muscles and glands.

### ***3.3.1.1 Processing of Information***

The nervous system will not be at all effective in controlling the human body if, for each bit of sensory information, the brain issues a motor reaction. Some of these sensory bits of information are unimportant, such as the pressure on the seat when a person is sitting, and the touching of clothing a person wears, and hence the brain discards such information. The brain selects the important sensory information and channels it into the proper motor regions of the brain to cause the desired response. That is, if a person places his hand on an oven or something hot, the desired response is to lift the hand and other associated responses such as moving the entire body away from the danger of the heat source. This immediate motor response is caused by a small fraction of the important sensory information received by the brain, the remainder of the information is stored for future control of motor activities and for use in the thinking process [Gregory, 87].

## **3.4 CEREBELLUM IN MOTOR CONTROL**

The cerebellum is vital for the control of all muscular activities such as crawling, creeping, running and walking. Loss of cerebellum leads to incoordination of these movements due to the loss of the planning function. The cerebellum's main function is to monitor and make corrective adjustments to the motor activities initiated by other parts of the brain. It does that by receiving continuous information from the motor control areas of the cerebellum on the desired motor programme and from the periphery to determine the status of the body parts.

As a result of feedback the cerebellum compares the actual movement with the movement intended by the motor system, and corrective signals are transmitted if necessary to alter levels of activation [Gordon, 1990]. It is important, however to note that the cerebellum does not initiate motor activities but rather plans, mediates, corrects, co-ordinates and predicts motor activities, especially for rapid movements. During rapid movements the continuous feedback by the cerebellum provides up-to-date and predictive information on body positions to other parts of the motor system [Ghez, 1986].

### 3.4.1 Learning of Movements

There are two types of movements, voluntary and involuntary movements. Voluntary movements may be classified into two main general categories, namely highly skilled such as those associated with highly specialised movements and normal every day life movements such as walking, running, talking and creeping and crawling for children. Voluntary movements, in general, in spite of their name, are not purely voluntary but are also controlled at a subconscious level. Voluntary movements of the two general classes and the intermediate stages between them, are part of a perceptual or conceptual motor process.

Proprioceptive and perceptive impulses provide the cortex with the data which it uses to initiate and guide these desired movements. In other words, the lateral section of the cerebellum is concerned with the overall control of movement of the entire body by having a planning and timing function working with the pre-motor sensory and association areas of the cerebral cortex (Guyton, 1991).

Involuntary movements are, however, not under cortical control. Their purpose is to maintain basic life processes of the organism. Reflexes are included in the involuntary class of movements. Once a movement is learnt, a sensory engram (a physical brain change supposed to take place as a result of experience, and to represent memories) is established in the sensory cortex and is used as a guide for motor system of the brain to reproduce the same pattern of movement.

If the pattern of movements and engram do not match, then appropriate muscles are automatically activated by additional motor signals to correct performance of the task. The motor engram cause a precise set of muscles to go through a specific sequence of movements to perform a task. The pattern can be performed without sensory feedback, but the sensory system still determines if the movement was performed correctly. Learning a pattern of movement is designated as a following process, where the ability of movement is not a natural inheritance but rather it is something that must be learned by effort.



Learning a movement is divided into structured learning and unstructured learning. Unstructured learning occurs when the subject tries to mimic the behaviour of others which usually happens at the early stages of the life of the subject. But structured learning can be undertaken at any stage regardless of age.

Whatever the activity is, standing, running, hopping or crawling, all the activity of the central nervous system finally ends with activating, or not activating, motor neurons to carry out a desired action. If however, the motor system fails to follow a desired pattern, this error is fed back to the sensory cortex and corrective signals are transmitted to the appropriate muscles.

This fact makes it essential to use organised, predetermined sets of movements, when executing the patterning techniques with brain injured children. The information from the motor cortex and from the periphery is integrated in the cerebellum, and then the intermediate zones of the cerebellum help to control voluntary movement, by utilising feedback circuits for the periphery and the brain. For example, during a movement, the muscles around a joint work according to a pattern of reciprocal innervation, so that when the limb is used for standing, the muscles around the joint tend to keep contracting together. Reciprocal innervation is organised so that as one group of muscles contract, the other group is relaxed. It is the same with the muscle used for breathing. As the muscles used for breathing-in contract, those used for breathing-out are relaxed.

#### **3.4.1.1 Frequency, Intensity, Duration**

Kottke, 1980, reviewed the literature about attaining skill proficiency and concluded that hundreds of thousands of repetitions create a conscious and a fair engram in which any necessary speed and force of performance can increase a reasonably capable motor engram with significantly increased level of sustained skill competence. Millions of repetitions create a near perfect motor engram of skill performance of every day skills such as walking, running, climbing stairs and driving. When these skills are learned they become automatic activities that are done without thought [Kottke, 1980]. Therefore, the implications for movement rehabilitation are

considerable, especially when the intention is to replace disorganised patterns of movement as in cerebral palsy patients, with normal patterns of movement. Therefore through effective repetitions a motor engram dominance can be established. As the new skill is learned and retained, then the central nervous system should be able to form the appropriate engram patterns, and to be stored in the long term memory [Gregory, 87].

### 3.5 SUMMARY

The central nervous system is responsible for every complicated and integrated set of communications that allows human to feel, think, respond and react. If disease or injury impairs the function of even the smallest subdivision of the biological systems, the consequences can be disastrous. The control of movements, in general, is a complex process which involves more and higher levels of the central nervous system depending on the degree of movement complexity. The process of learning a new movement or skill can be slow and takes time and practice to achieve a satisfactory level, especially for those who suffer from some form of brain injury. But once this movement is learnt it becomes more automatic with time. It may be necessary sometimes to adapt to minor alterations depending on the changing environment. Since the nervous system is a totally integrated system, information is constantly being gathered on the status of the body parts and new skilled are developed by the subject, and are often compared with past movements stored in the central nervous system. The central nervous system should thus be able to utilise these new movements or skills with less effort.

The one certain factor in achieving success, in the learning and practising of new movement or skill is an adequate error free repetition of movements to achieve the required level of competence and to allow a suitable long term motor engram to be formed. All learning processes from the stage of conscious control of movement to non conscious control of movement are dependent upon sensory feedback to correct any error. Therefore, structured learning is the most common form of learning in which special emphasis must be put on sustained motivation. Hence, a Patterning

Machine should be designed to ensure error free performance, and to reinforce correct movement by repetition and encouragement, i.e. during input/output sessions.

During input sessions, the required sets of movements would have to be put into the patients by such a Patterning Machine. And during the output sessions, the patients must be encouraged through their own efforts to produce appropriate bodily movements. The patients can, if necessary, be initially given some partial assistance by a Patterning Machine, during such output sessions.

# Chapter 4

## INVESTIGATION OF USER REQUIREMENTS

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*'There is nothing in the world more powerful than an idea. No weapon can destroy it; no power can conquer it except the power of another idea.'* James Roy Smith, (1775-1893).

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### 4.1 INTRODUCTION

To investigate user requirements, it was essential to critically study and analyse the previous work done in the area of rehabilitation and robotics. Over the last forty two years, there has not been sufficient effort to help the brain injured patients restore, enhance or maintain their natural mobility. Applications of mechanised devices have been strongly focussed on the automotive industry and consequently much of the early research work was directed into this area. Most rehabilitation robotics work is concentrated on aiding handicapped patients, where robotic arm manipulators have been designed and constructed to make life easier for wheelchair users. Therefore there is still a critical need for reserach into mechatronic devices, integrating electrical, electronics and computing technologies with mechanical engineering, for application in the remedial process for brain damaged patients, and especially for patients with cerebral palsy who have never crept, crawled or walked, and those who have gait related difficulties.

In the area of rehabilitation robotics and mechatronics for brain injured patients many previous designs possess some basic flaws, e.g. too expensive, not ergonomically suitable, too difficult to assemble and operate.

It is extremely important to include as fully as possible, the needs of brain injured patients from the initial stages of the design process. Such a design approach needs to be based upon a detailed consideration of human factors and ergonomics data as applicable to rehabilitation robotics and mechatronics for brain injured patients. To the author's knowledge, there is an absence published information on such detailed considerations of human and ergonomics factors, development profile and analysis of the patterning techniques. Therefore the author has conducted and presented (if available) such a detailed consideration below.

## **4.2 PRELIMINARY DESIGNS**

The preliminary design specifications, written before the study was completed, contained very little information regarding the age group and the size of the machine. Because of the different sizes and shapes of humans the possibility of one patterning machine which covers all ages and all sizes of patients was ruled out. It was therefore necessary to establish a link between the most important tasks, as defined by the developmental chart, Appendix B, the difficulties that the helpers might experience when patterning patients and the most feasible tasks the machine can reasonably perform without compromising the system integrity and within a minimal cost. The results of the study here aided in the formulation of the final design specification which is detailed in Chapter 5.

### **4.2.1 Design I**

This design was an instant reaction from seeing brain injured children being patterned manually on a bench at the British Institute for Brain Injured Children, BIBIC. Design I as shown in Figure 4.1 consists of four adjacent units fixed on three bars of 100 mm wide, 50 mm thick and 1000 mm long placed over an equal distance

of 2000 mm. Each unit is 200 mm wide, 5 mm thick and 2000 mm long, equipped with three sets of small teeth to be used for joining the units to the three horizontal bars. Each bar has a predetermined number of holes to adjust units according to the patient's size. Each unit has two platforms provided with hand, feet and knee straps to fasten the patient to units. One head-cradle (not shown) supports the head of the patient. Each unit is to be individually driven by a suitable small motor and controlled via a key pad operated by any ordinary person in the home environment.

#### 4.2.1.1 Operation of Design I

The child is placed on the machine in the crawling position, i.e. cross pattern crawling. The child right hand is fastened on platform 1 and right leg fastened on platform 4. Platforms 7 and 6 are for left hand and leg respectively. To provide power to the patterning machine, a motor is connected to each platform via a chain. As the motor is powered the platform moves a specified distance forward, e.g. platform 1, causing the right arm to move. At the same instant of time platform 6 moves causing the left leg to move forward the same distance the right arm has moved. As both the right arm and left leg reach the desired distance, the left arm on platform 7 and the right leg on platform 4 start moving until the desired position set by the therapist (depending on the stiffness of the patient) is reached. Then the machine reverses backward to its original position and the cycle continues, initially at a very low speed. The speed of movement can be increased if desired.

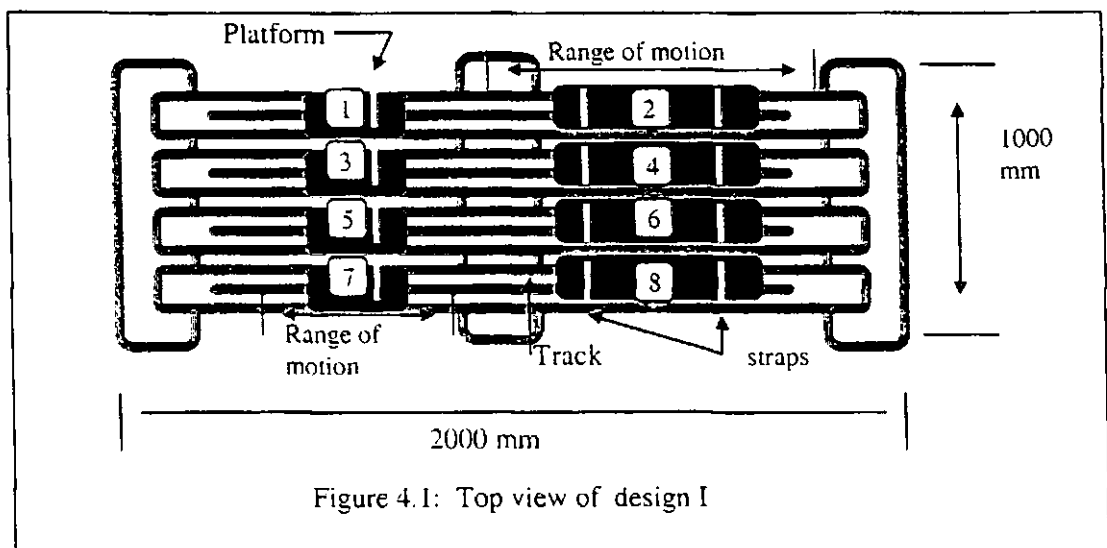


Figure 4.1: Top view of design I

#### *4.2.1.2 Analysis of Design I*

This design does not provide all the required patterning techniques. It provides homolateral and cross pattern crawl, and walking. It could not provide the essential patterning techniques as defined by Doman, in 1960 such as homolateral and cross pattern creep. From the safety point of view, the tracks on the platform may cause injury to the child should any of his limbs come loose.

#### **4.2.2 Design II**

Considering the fact that patients are of different sizes and ages with 90 % of brain injured patients being children, and also to some extent to provide for the different types of patterning techniques, another design to cope with different sizes and types of patterning is offered. Design II shown in Figure 4.2, consists of 6 units to provide for homolateral and cross pattern creep in addition to other types of patterning. Each unit consists of a small platform 100 mm wide, connected to a lead screw shaft driven by a motor. The units are linked together by a side hook, and the maximum allowable spacing distance between any of the units is 5 mm. As the lead screw shafts move, the platforms move, depending on the issued commands, by a predetermined distance.

##### *4.2.2.1 Operation of Design II*

The child is to be placed on the units in the prone position. To start the motion of the machine the child must be fastened with adjustable straps. If cross patterning creep is to be performed the child's right arm is fastened to platform 1 and the child's right foot and knee is fastened to platform 2. The body breadth is placed on platforms 3 and 4 with a harness supporting the child's body. The patient's body should be slightly touching the platforms.

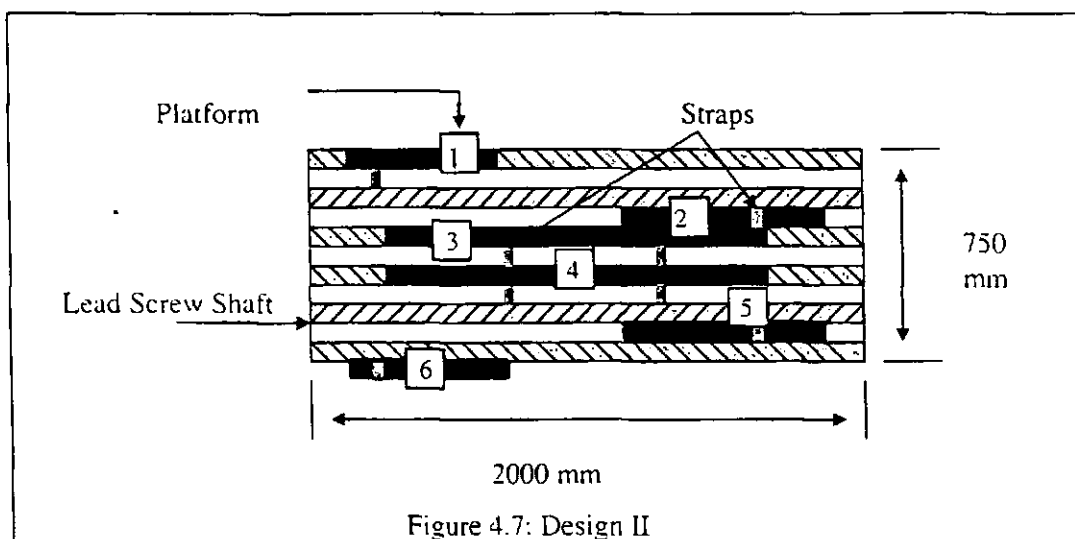


Figure 4.7: Design II

The left leg and arm are fastened to platforms 5 and 6 respectively. The programme loops to a safety check. Once all the instructions are correctly fed in, the program indicates that the motor is ready to start moving the platforms. As the right arm and left leg move a predetermined distance, the left arm and the right leg start moving the same distance and platforms 3 and 4 start moving when platforms 2 and 6 reach half the predetermined distance. Then the cycle is repeated several times.

#### 4.2.2.2 Analysis of Design II

Even though this design covered all of the required patterning techniques, it did not provide continuous movement of the limbs of the child. The lead screws are very stiff, slow to get into desired positions, too expensive for this type of application, and experience fretting which is a common problem with lead screws. One other disadvantage with this type of system is the safety aspect especially when dealing with humans (brain injured children).

#### 4.2.3 Designs I & II, An Overview

Analysing the pros and cons of designs I and II has led to the conclusion that a third and final design is needed and it also showed the possibility of mimicking the real creep and crawl. Mimicking the movements normal healthy children would naturally experience has prompted a detailed study of human movements with emphasis on



creeping crawling and walking. A proposed design by kavina was later adopted as the final design of this research programme. Studying the creep and crawl of normally developing children and the related ergonomics of the human body has highlighted the following points:

- In normal healthy children, crawling is initially commenced without any pattern or synchronisation between the limbs followed by crawling homologously in which arms and legs are moved in a frog-like sequence.
- After the children have learned how to crawl homologously, the children then learned how to crawl in a homolateral pattern in which the children moved the right arm and leg together and the left arm and left leg together but with no sequential action with the opposite arm and leg.
- After the children had achieved the homolateral pattern, they then learned the cross pattern arrangements in which the children tried to move forward with the right arm and left leg followed by reversal of this sequence with left arm and right leg.
- Once the cross-pattern creep arrangement had been achieved, the children were then ready for crawling and subsequently walking.

Note, however that from one child to the next, there can be variations with respect to the above points.

The proposed idea of using an adjacent set of conveyor belts to stimulate brain injured child [Kavina, 96], appears to mimic the instinctive development of a normal child. Normal children experience these movements in early life, developing the necessary skills of creeping crawling and walking. Brain injured children do not have any instinct to develop these co-ordinated movements unaided. It has been demonstrated by Doman, 1960, and others as presented in 2.3.1.5, that repetitive external manipulation of the limbs in the proper synchronisation for various movement techniques or patterns teaches brain injured children the induced limb movements.

Once the homolateral patterning technique has been learned by external manipulation of the limbs, the patient is ready for the cross-pattern technique which prepares the child for crawling. The proposed design, its specifications and analysis of its functional performance, will be discussed in more details in Chapters 5 and 6.

### 4.3 MEASUREMENTS AND ANALYTICAL ANALYSIS OF THE HUMAN BODY

#### 4.3.1 Measurements Of Dynamic Human Body Dimensions

Although human beings do vary widely in size and shape, their variation follow certain patterns. The fact that groups within the population vary less than the population as a whole, simplifies the goal of fitting 95 % of the population within a certain group [Damon, 66 ]. All the following measurements made are within an accuracy range of  $\pm 2\%$ .

##### 4.3.1.1 The Human Arm

The human arm consists of the shoulder joint which is attached to the torso, the upper arm which extends to the elbow joint, the lower arm which extends to the wrist and finally the hand itself consisting of four fingers and a thumb. The human arm has 7 degrees of movement and the hand has another 14, making a total of 21. The ranges of arm motion are given below in Table 4.1, with the position of reference at  $0^\circ$  defined as that taken up by the upper limb hanging downwards at the side of the trunk.

Table 4.1: Ranges of shoulder movements [Damon, 66 ]

Shoulder (Deg.)	Range (Deg.)	Terminology
+180 to -50	230	Flexion-Extension
+30 to -180	210	Adduction-Abduction
+80 to -95	175	Lateral-Medial (rotation)

Table 4.2: Ranges of elbow movements [Damon, 66 ]

Elbow (Deg.)	Range (Deg.)	Terminology
+145 to 0	145	Flexion-Extension

Table 4.3: Ranges of wrist movements [Damon, 66 ]

Wrist (Deg.)	Range (Deg.)	Terminology
+15 to -45	60	Adduction-Abduction
+65 to -73	138	Flexion-Extension
+90 to -180	270	Pronation-Supination

Table 4.4: Average human arm lengths and weights

Age range	Upper arm	lower arm	Hand
Children (0.5 to 13.5 years)	206 mm	176 mm	154 mm
Adults (14 years on)	282 mm	254 mm	191 mm
Children (0.5 to 13.5 years)*	0.38 Kg	0.24 kg	0.18 kg
Adults (14 years on)*	2.5 Kg	1.5 kg	0.6 kg

\* The body segment masses [Damon, 66 ] are directly proportional to the individuals body mass.

The human arm lengths and weights in Table 4.4 were obtained by measuring children and adults in the London area. Special care was taking when selecting the sample which included ethnic minorities. The ratio of the length of the upper arm to the lower arm is thus 1.2:1 and the ratio of the arm length (upper and lower arm) to the hand length is 2.8:1. These characteristics can have a very significant impact on the performance and working envelope of a manipulator for remedial treatment. Taking the case where the lower arm is fastened to the moving belt (manipulator), the actual movement of the arm is in a circular manner. In reality it may not be possible or practical to make the arm move in a linear motion without restricting the movement of the arm.

### 4.3.1.2 The Human Leg

The human leg consists of a hip joint which is attached to the torso, the thigh (upper leg) which extends to the knee joint, the leg (lower leg) which extends to the ankle and finally the foot itself consisting of five toes as shown in the Table below:-

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Table 4.5: Ranges of ankle movements

Ankle (Deg.)	Range (Deg.)	Terminology
+35 to -38	73	Flexion-Extension
+24 to -23	47	Adduction-Abduction

Table 4.6: Ranges of knee movements

Knee (Deg.)	Range (Deg.)	Terminology
125	125	Flexion (Prone)
+35 to -43	78	Medial-Lateral (Rotation)

Table 4.7: Ranges of hip movements

Hip (Deg.)	Range (Deg.)	Terminology
113	113	Flexion
+31 to -53	84	Adduction-Abduction (prone)
+39 to -34	73	Medial-Lateral. (Rotation) (prone)

Table 4.8: Average human leg lengths and weights, [Dreyfuss, 74]

Age range	Upper leg	Lower leg	Foot
Children (1 to 13.5 years)	289 mm	280 mm	180 mm
Adults (>14 years)	435 mm	426 mm	243 mm
Children (1 to 13.5 years)*	1.36 kg	0.71 kg	0.41 kg
Adults (>14 years)*	7.47 kg	3.91 kg	1.13 kg

\* The body segment masses [Damon, 66 ] are directly proportional to the individuals body mass.

The above measurements were also confirmed by measuring children and adults in the London area. The ratio of the length of the upper leg to the lower leg is thus 1.02:1 and the ratio of leg length (upper and lower leg) to the foot length is 3.2:1. These

characteristics can have a very significant impact on the performance and working envelope of the manipulator for remedial treatment.

#### 4.3.1.3 The Human Head

The human head consists of the skull and the neck. The ranges of motion are given below in Table 4.9.

Table 4.9: Ranges of neck movements, [Damon et al. 66]

Neck (Deg.)	Range (Deg.)	Terminology
+67 to -77	144	Flexion (ventral-dorsal)
41	41	Flexion (right or left)
+73 to -74	147	Rotation prone (right-left)

#### 4.2.1.4 Muscle Strength

Strength is defined as the maximum force that muscles can exert isometrically in a single voluntary effort. Therefore the muscles of the body act as one unit in a desired body position to transmit forces to objects outside the body to control, push or pull an object. It is vitally important for a design engineer to determine maximum and optimum control resistance and the required forces to perform a manual task. e.g. the patient will resist the moving belts, therefore the force applied should not exceed the instant force exerted by the patient. However, in this case operational levels affecting comfort and efficiency should be low enough to prevent fatigue or discomfort, but still high enough to prevent inadvertent operation of the control to provide enough force to control movements.

Measuring the strength of the human body is performed using spring steel dynamometers, electrical gauge dynamometers and strain gauge dynamometers. Most of the studies available to date have used a series of samples of at least fifty subjects. Data from various strength studies are not always directly comparable, because of differences in measuring techniques such as a subjects' body position, types and amount of movement permitted, motivation, kind of dynamometer used and the

number of kinds of subjects. In the case of a brain injured patient, patients are placed in prone position to be patterned, therefore measurements of forces exerted by the patient while laying prone are measured. The ranges of the maximum forces the human arm can exert on a vertical hand grips are given below in Table 4.10.

Table 4.10: Average forces exerted by the human arm, [Damon, et al, 66]:

Movement	Elbow angle (Deg.)	*Right arm 95% tile (N)	*Left arm 95% tile (N)
Push	180	525	494
Pull	180	547	516

\* Usually the weaker hand is 9/10 of that of the favoured hand.

When measuring muscle strength of the human body, a good rule of thumb for applying the guidelines to females is that adult females generally are about one-third weaker than adult males. Table 4.11, lists the ranges of strength of adults and children [Dreyfuss, 74]. These tabulated forces were later confirmed using a custom made strain gauge (details of the design are in section 4.6.2.1) where each person was asked to lie in the prone position and to pull and hold the metal bar and then push and hold the metal bar for a period of 30 s.

Table 4.11: Ranges of strength of adults and children [Dreyfuss, 74]

Age or Category	Push	Pull
3 years	93.9 ± 2 N	89.4 ± 2 N
5 years	138.8 ± 2 N	134.8 ± 2 N
7 years	274.5 ± 2 N	270 ± 2 N
10 years	338.5 ± 2 N	333.6 ± 2 N
Weak man	115 ± 2 N	102 ± 2 N
Weak woman	75 ± 2 N	66 ± 2 N
Strong man	564 ± 2 N	536 ± 2 N
Strong woman	369 ± 2 N	360 ± 2 N

However, humans cannot maintain maximum force application (pushing and pulling) for extended periods of time. Strength capabilities when individuals are in prone positions are provided in Table 4.12 [Dreyfuss, 74].

Table 4.12: Instant and sustained forces of humans, [Dreyfuss, 74]

Terminology	Push	Pull
Instant force	111.2 ± 1 N	106.2 ± 1 N
Sustained force	58.1 ± 1 N	64.5 ± 1 N

- *Effect of age and gender on strength*

Generally adult males are about one-third stronger than adult females. Since brain injury is most likely to occur in new born babies and pre-school children, the author concentrated on the effects on strength of children age six months to thirteen and half years old. Usually there is an adequate development of strength during early age 1 to 13.5 years and a rapid development of strength between the ages of 14 to 19. Moreover this development slows down somewhat between the ages of 20 to 25. This is followed by a slow increase between 25 to 30 years of age. Normally strength decreases by 10% by the age of 40, 15% by the age of 50, 20% by the age of 60 and at least 25% by the age of 65 [Woodson, 81].

- *Effect of acceleration*

There are insufficient data on the muscular forces that can be exerted under various types of acceleration. Accelerations up to 5 G (gravitational force) does not influence strength unless the forces are applied over long periods. As muscular forces acting in the direction of acceleration are increased, those acting against the direction of acceleration are decreased and those exerted perpendicular to the direction of acceleration are least effected. Forward acceleration and backward acceleration of 2 G are tolerable at least for up to 24 hours [Woodson. 81].

#### 4.2.1.5 Dynamic Measurements

The following Tables show the most important measurements which were taken to set up the kinematics arrangement of the Patternner Machine. The design arrangements is to be suitable for 95 % of the population of brain injured patients. The following Tables 4.13 and 4.14 contain data that divided the patients into two groups, adults

from 13.6 years old and above and children 13.5 years old down to 6 months old babies. Measurements of the children were conducted in junior, infant and nursery schools as well as at the British Institute for Brain Injured Children headquarters in Somerset, England. Most of the adult population measurements were obtained from Damon, 66 and others. Measurements in Table 4.13 were taken under the following test conditions: The subjects were divided into two equal groups. Each group has at least 50 % females and at least 30 % ethnic minorities, i.e. Blacks, Asians ... etc. Each subject was asked to take the positions shown in Appendix A. The subject was first asked to stand erect, arms at sides to measure the maximum body depth. Then to measure the over head reach, the subject was asked to lift the right hand to the highest position attainable without strain. After the Kneeling height and length and Crawling height and lengths were measured, the subject was asked to lie in the prone position and extend arms and feet as much as possible.

Table 4.13: Measurements of the human body for children

Measurement mm (Children)*	Number of subjects	5%tile	Mean	95%tile
Maximum body depth	80	145.3	189.5	183.8
Max. body breadth	80	291	357	423
Overhead reach	80	960	1290	1630
Kneeling height	80	402	562.8	723.4
Kneeling length	80	60.6	91.6	1220.5
Crawling height	80	371.1	521.1	671.2
Crawling length	80	612.2	910	1207.8
Prone height	80	262.8	330	397.2
Prone length	80	1123.7	1477.2	1830.6

\*Children age 6 months to 13.5 years old.



Table 4.14: Measurements of the human body for adults, [Damon, 66 ]

Measurement mm (Adults)	Number of subjects	5%tile mm	Mean mm	95%tile mm
Maximum body depth	40	256.5	292.1	330.2
Max. body breadth	40	447.5	530.9	579.1
Overhead reach	40	1950.7	2095.5	2247.9
Kneeling height	40	754.4	812.8	876.3
Kneeling length	40	955	1092.2	1221.8
Crawling height	40	665.5	721.4	774.7
Crawling length	40	1252.2	1351.3	1478.3
Prone height	40	312.4	368.3	416.6
Prone length	40	2151.4	2288.5	2433.3

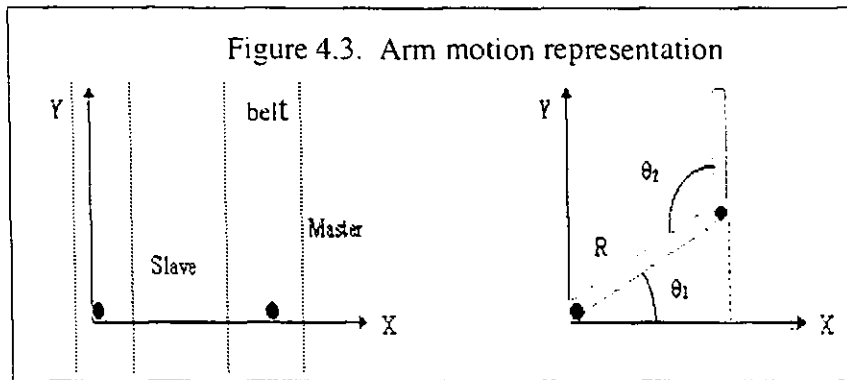
### 4.3.2 Developments of Mathematical Expressions of Body Joints

Body joints are formed whenever two or more bones articulate (immovable joints are not relevant here). The most important moveable joints considered are hinge joints (knees), pivot joints (elbow) and ball and socket joints (shoulder and hips). The range of joint motion is determined by the body configuration, by the attached muscles, tendons and ligaments and the amount of surrounding tissues, all of which vary to some extent from person to person and from joint to joint. The main reason behind the development of mathematical equations of the movements of arms and legs is that the range of movement of one part of the body is affected by the position or movement of neighbouring parts. e.g. lower arm rotation can be considerably increased if shoulder movements are added to those at the elbow. The mathematical analysis below concentrates on prone position movements which may not coincide with those made in any other position.

#### 4.3.2.1 Shoulder and Elbow Movements

The lower arm of the patient is strapped from the wrist to a moving belt. The movements of the shoulder and elbow are brought about by the moving belt which is attached to a driving pulley. Consider the lower arm to be called the master (the

controlling element) where the upper arm is the slave (the controlled element) as shown in Figure 4.3. Since only the lower arm is fastened to the moving belt, the upper arm does not have the same angular limitations and allows transmission ratios other than one to one. The connection between the upper and lower arm of the patient is such that when the lower arm (master) follows a straight vertical line, the upper arm (slave) describes an ellipse length of a small radius, Where only  $\theta$  and  $R$  can be altered by the motion of the belt when the controller actuates the motor. Such distortion of movement does not trouble the patient, as long as the angle between the lower arm, master, and the corresponding upper arm, slave, displacement does not exceed  $\theta$ .

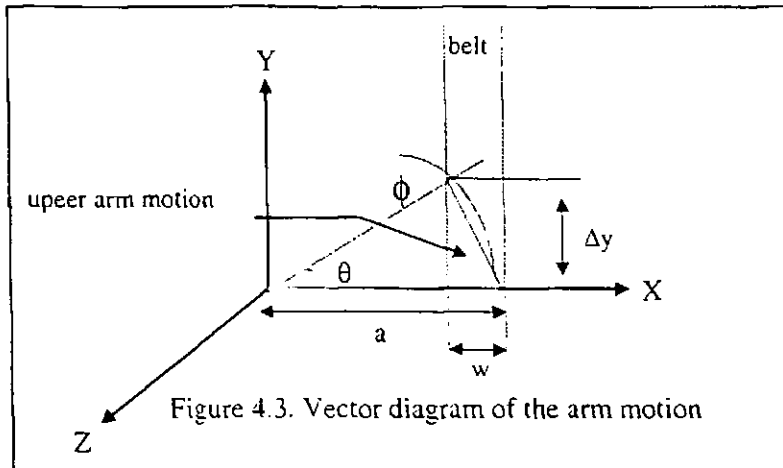


$$R^2 = X^2 + Y^2 \quad (4.1)$$

$$\theta_1 = \arctan Y/X \quad (4.2)$$

#### 4.3.2.2 Analysis of the Upper Arm

In order to describe the motion of the upper arm moving on a flat surface, it is considered appropriate to develop mathematical equations to show the motion of the controlling arm (lower arm) accompanied by the motion of the controlled arm (upper arm). As shown in Figure 4.4, the initial position of the arm is at  $(a, 0)$  and the final position to be reached is  $(a - w, \Delta y)$ , where 'a' represents the magnitude of the upper arm and 'w' is the width of the belt. Here it must be noted that the lower arm, which



is the master arm is restricted to move only in a straight linear motion because it is fastened to the moving belt, while the slave arm, upper arm, will be moving in a curvilinear motion. Note also that the lower arm is initially at right angles to the upper arm. Therefore the angle ' $\theta$ ' which represents the angle between the initial position of the upper arm and the final position of the upper arm can be given as in equation 4.3 by

$$\theta = \arccos(a - w / a) \quad (4.3)$$

and the angle  $\phi$ , which represents the angle between the upper arm 'slave' and the lower arm 'master' is given by equation 4.4:

$$\phi = 90^\circ + \theta \quad (4.4)$$

Then the displacement (motion of the upper arm in circular manner) is as given in equation 4.5:

$$\Delta y = a \sin \theta \quad (4.5)$$

Substituting equation 4.5 into the final position,  $(a - w, \Delta y)$ , then the angle ' $\theta$ ' is as given in equation 4.6.

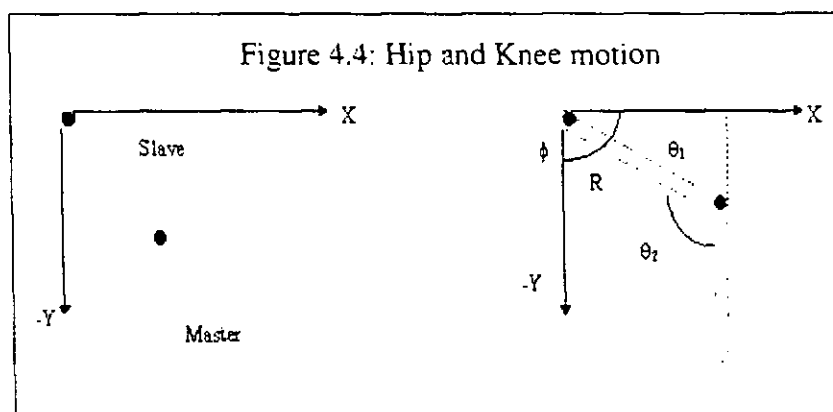
$$\theta = \arccos(a - w / a) \quad (4.6)$$

Equation 4.6 should be used as a guideline for the maximum displacement of the arm. Note however that the belt width is 100 mm and that the angle 'θ' should never exceed the calculated value. The final desired position for any patient in terms of the displacement is given in equation 4.7.

$$\Delta y = a \sin [\arccos (a - w / a)] \quad (4.7)$$

#### 4.3.2.3 Hip and Knee Movements

The lower leg of the patient is strapped to the moving belt from the ankles. As the lower leg (controlling leg) moves in a linear motion, the upper leg (controlled leg) moves in a circular arc motion. The angle of movement will be restricted to a value of  $\theta_1$  as shown in Figure 4.3. The altered motion does not trouble the patient as long as  $\theta_1$  is not exceed.

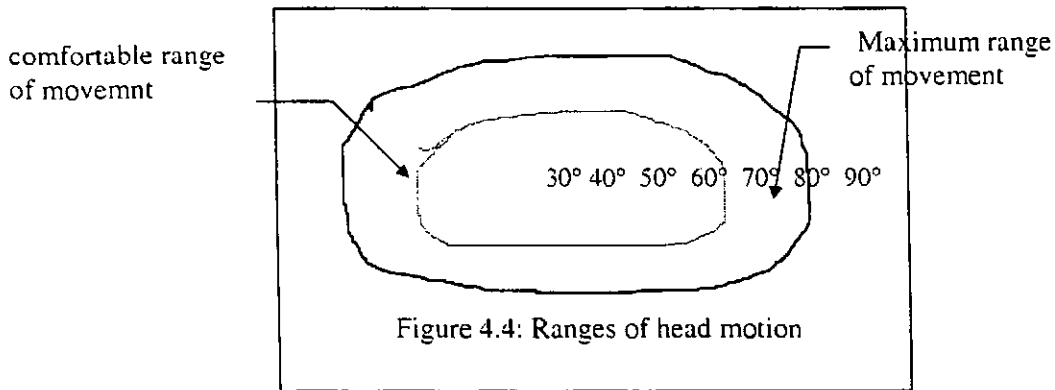


#### 4.3.2.4 Analysis of the Upper Leg

The motion of the upper leg is similar to the motion of the upper arm described above in 4.2.2.3. The only real difference between the two motions is the fact that the upper arm starts its motion at (1, 0) and the upper leg at (-1, -1).

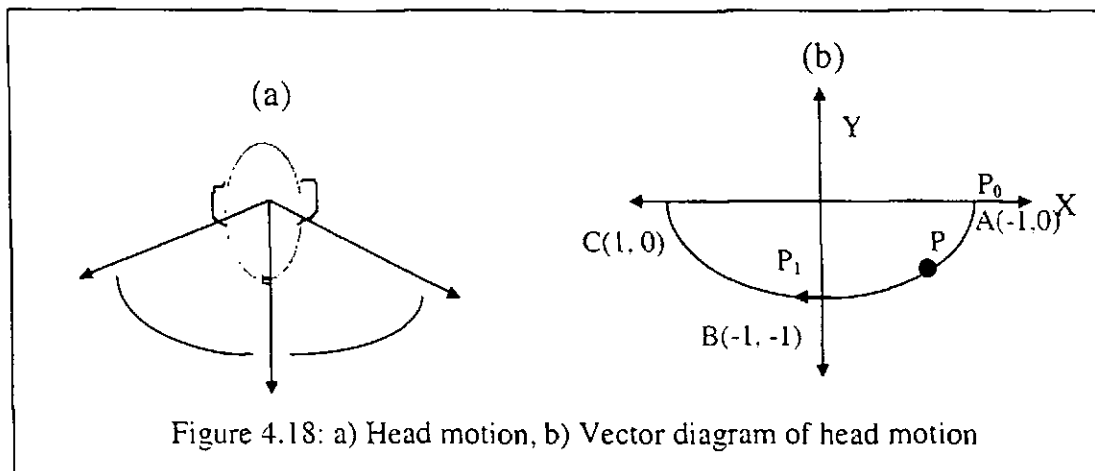
#### 4.3.2.5 Head Movement

The head does not move in a circular arc as commonly supposed, but follows an elliptical curve. The solid line in Figure 4.4 shows a maximum turning reach of  $85^\circ$ , whereas the dotted line shows that the head can be comfortably turned in either of the two directions without causing any strain to the patient (within the limits of comfort) to a maximum rotating angle of  $69^\circ$ .



#### 4.3.2.6 Analysis of the Head

Figure 4.5 shows the head of the subject in the prone position (the subject is facing down). As the patient is being patterned the head has to be moved to right and to left with respect to the movement of the rest of body, i.e. in homolateral patterning, as the right arm and left foot move forward the head is turned to the right. To develop a mathematical expression for the head movement, let the head start its motion at point  $A(-1, 0)$  where  $\theta = 0$  as shown in Figure 4.5b. Moving along  $AB$  to point  $B(-1, -1)$ ,  $\theta$  varies from  $0$  to  $-\pi/2$  and continues to point  $C(1, 0)$  where  $\theta$  increase to  $\pi$ . Here the kinetic energy of the head at the start of motion is equal to  $0$ , and  $v = 0$ , then the work done by gravity is  $mgy$ .



$$\therefore mgy = 1/2mv^2 - 1/2 m(0)^2 \quad (4.8)$$

$$v = ds/dt = \sqrt{2gy} \quad (4.9)$$

$$dt = ds/\sqrt{2gy} = \sqrt{1 + (dy/dx)^2} dx / \sqrt{2gy} \quad (4.10)$$

#### 4.3.3 Lessons Drawn From Human Measurements And Their Analysis

- Measurements were made under similar conditions regarding the positioning and movements that the Patterner Machine would be expected to perform.
- Patterning involves the whole body, especially the legs and arms of the brain injured child. Accurate measurements of arms and legs as well as the range of rotation of the shoulder, arms and knee joints were undertaken.
- Dynamic body measurements referred to in Appendix A are related to the purpose of patterning and may not be used as standardised body measurements.
- Measurements in Tables 4.1 to 4.14 were useful in determining the size of the platforms and the range of movements and rotation of the arms, legs and head.

- The analysis helped realise the fact that the movement of any particular part of the body depends on other movements taking place concurrently, which may or may not be in the same direction or move in the same orientation.
- Movements capabilities of brain injured patients, cannot simply be assumed to be identical to the movement capabilities of normal patients.

#### **4.4 PRELIMINARY DESIGN REQUIREMENTS**

A preliminary design specification was written in the initial stages of the study. It contained very little information regarding the length, size of patients and human movements, force interaction, speed and flexibility. It was decided to have six individual units. Each unit consists of an endless belt, two pulleys and a platform. Each unit is to be driven independently of the other units [Kavina, 96], using an adaptable control strategy. Depending on the type of patterning a minimum of two units for walking and a maximum of six units for cross patterning creep are to be used. Before carrying out the idea of this novel design, research into almost every aspect of the human body statically and dynamically was needed and a literature review of world rehabilitation robotics was undertaken which led to the formulation of the final design specifications presented in Chapter 5.

#### **4.5 INVESTIGATIONS AND ANALYSIS**

The investigation revealed that about 90% of brain injured patients are children. Very few of the designs available to date were specifically aimed at treating the problem of brain injury. Most designs were aimed at helping the brain injured cope with the problem. To date sixty-nine systems have been provided for use by severely disabled people on a regular basis, where the majority of these people are suffering from cerebral palsy [Topping, 95]. Only a few of these systems have a degree of relevance to the remedial treatment of brain injured children.

Researchers have looked at the use of electromechanical structures and dampers to limit the unintended movements of brain injured patients [Downing, 90]. Most of these electromechanical devices were used to test reflex functions, such as when Hammond in 1954 and Lee and Tatton in 1982 investigated muscular reflex responses to limb perturbation where the subject must resist a constant torque produced by an electric motor. Most of these mechanical devices lack the necessary robustness and automation to carry out the patterning techniques as an input-output exercise which is an essential external aid needed to stimulate the uninjured brain cells of the patient. These techniques applied only to a particular strategy of movement, i.e. the hip extensor muscles.

One of the main objectives of this investigation is to determine whether patterning techniques initiated by Doman, could be analysed and characterised in such ways that the use of a mechatronic device could be used to pattern and consequently enable brain injured patients to restore or enhance some of their natural mobility, and to make their intended control actions to be as normal as a person with no apparent motor impairment, i.e. normal child.

However, any complete mechatronic system requires a team effort, involving patients, operators and programmers, an assessment of patients' and operators' capabilities, selecting an appropriate interface for controlling the automated system, development of software for commanding the manipulator under operator control with safety limits set by the programmer together with the medical team advisor to ensure no fatigue and no undesirable force actions to the patient. The operator must understand the capabilities and limitations of the system, the system must be very simple so that an ordinary person can operate it effectively, the mechatronic system must be a complete unit that is programmed to control and safely take over the tasks set by any of the institutes concerned, the system must be flexible enough to be used at the patients' home and must be simple to assemble and above all user friendly. The system must have equipment which embodies primary protection such as limits, stops, guards and/or adequate fail safe features so as to prevent accident or injury to the operators and patients, since secondary protection provided by sensors and software, alone is not adequate to ensure intrinsic safety.

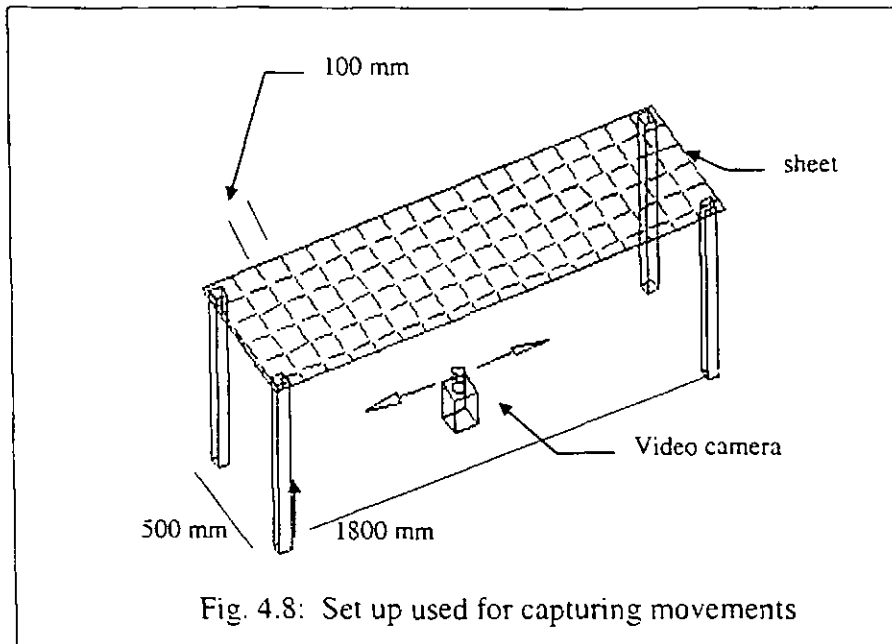


This investigation has revealed that it is important to come up with a good design for the remedial treatment of brain injured patients, since most devices available to date, are not used for patterning the whole body of the patient. Instead they are mainly used as exercising machines for one particular limb of the human body.

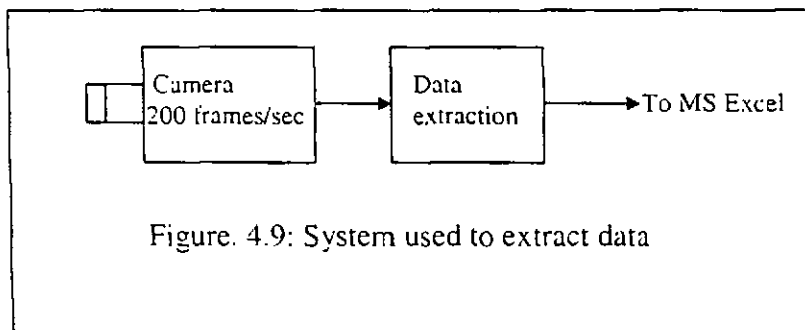
The design specification was the first step in the design process, whereby the most important tasks were translated into a form that can be accomplished. The specification was the integral part of the design process, which began with the preliminary design specification before culminating with the final design specification. The final design specification is not necessarily the last specification to be written, as this may have to be changed during the modification / redesign phase of the project.

#### **4.5.1 Experimental Measurements and Analysis**

The scientific approach as applied in this research program has been characterised to describe the movement of a brain injured patient in the prone position only. Since it was not possible to bring brain injured patients to the experiment site and considering the fact that brain injured children were to be patterned as normal children who would instinctively develop the appropriate limb movement, therefore, a high speed video camera of 200 frames per second was used to record the movement of normal children. The results and analysis of the recorded movements are presented in this Chapter. Figure 4.8 shows the set up that was used at the Road Safety laboratory (RSL) in Middlesex University, Hendon site. The children were placed in the prone position on a strong grided see through sheet and were then asked to move forward until the end of the sheet was reached. The camera was capturing the movements from underneath the sheet where the knees and the elbows of the subject were clearly visible as well as the body breadth. The children were asked to perform homolateral and cross pattern creep and crawl and walking several times. All the movements were captured using a 200 frames per second video, and then fully analysed.



The analysis concentrated on the movement of the elbow and the knee since the wrist and the ankles would be strapped if the child were to be placed on the Patterning Machine. The analysed data were then fed to MS Excel to plot the movement of the children. Figure 4.9, data listed in Appendix F.

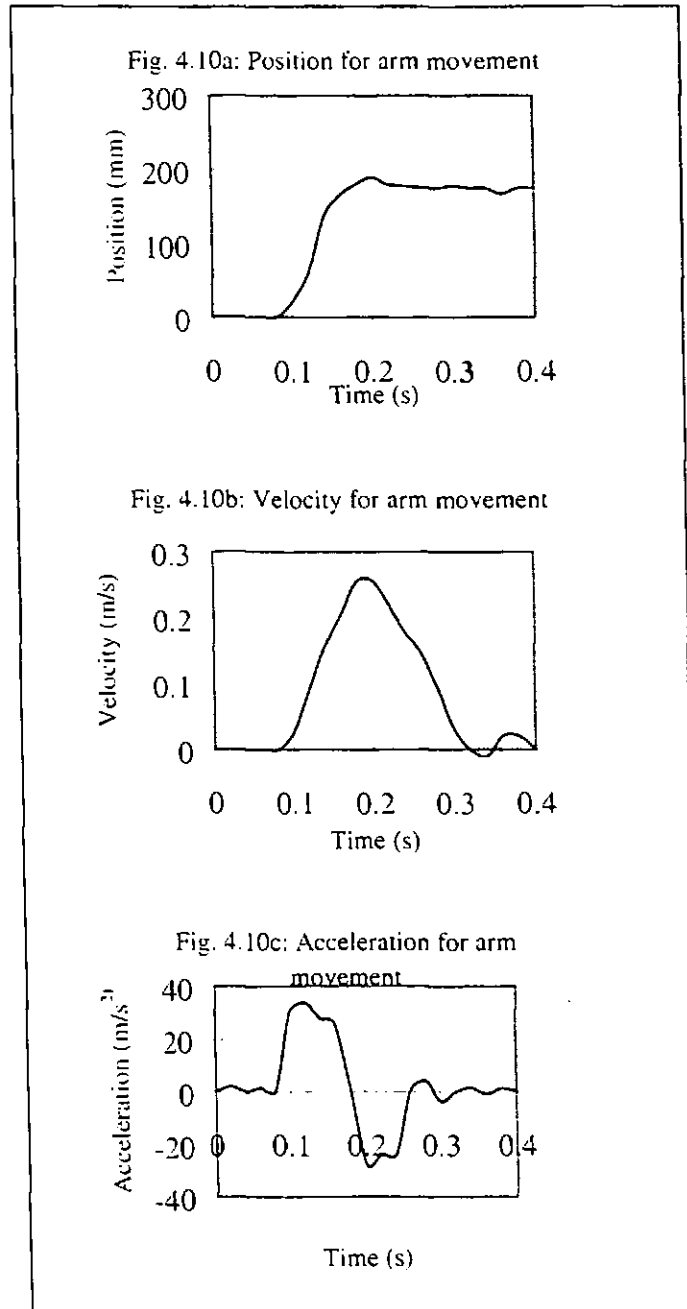


#### 4.5.2 Kinematic Measurements

The aim here is to focus on the movement itself as the name kinematics implies. Here a series of motions were studied without regard to the force and masses involved. Differences in limb length and movement are important to this type of analysis, but differences in the limb cross-sectional circumferences or masses are not. The child is placed on the movement capturing table shown in Figure 4.8, in the prone position.

The positions of critical locations on the arm/shoulder and knee/leg were plotted at intervals of time during the execution of creeping and crawling motion. This was accomplished as shown in Figure 4.9, by analysing the high-speed film. It required recording the position of each critical point on each frame of the film. Although a number of instruments are available which will locate special marks or sensors placed at the critical locations of the moving body, the restricted budget did not allow obtaining such an instrument. Determining the position of the limb segments in space was the first step towards determining the rate of change of location with time, or in other words velocity. In turn, the rate of change of velocity with time is referred to as acceleration.

Figure 4.10a, b and c, show the kinematics data of the arm movement. This data was obtained by using the set-up shown in Figure 4.8. These recordings of position, velocity and acceleration are a clear and simple description of the movement dynamic of the subject. Here the subject was attempting to advance forward three step sizes, two squares on a custom made grid table, at a normal pace of 200 mm each. The displacement recording in Figure 4.10a, indicates the subject began to move at approximately 0.75 seconds into the recording. The largest amplitude was recorded at 190 mm, after which the subject made a small correction back to the target. The velocity recording indicates that the subject increased the velocity of the movement for the first 80 ms, Figure 4.10b, achieving a maximum velocity of approximately 0.26 m/s. The negative velocity can be explained, as the subject tried to reduce the step size to meet the target. The acceleration recording in Figure 4.10c, indicates that the greatest acceleration occurred very early in the movement and the point of greatest deceleration occurred as the subject reached the target. Note, however that at the point of greatest velocity there was no acceleration. This was because the subject was in transition from acceleration to deceleration.



### 4.5.3 Actual Creep, Crawl and Walking

The second phase of the experiment in the RSL laboratory was set up to study and analyse the actual creep, crawl and walking. Initially a sample of five children were selected and were asked to perform crawl, creep and walk randomly (without giving them instructions to perform homolateral or cross pattern actions), then later the same

group of children were asked to perform homolateral and cross pattern creep and crawl in addition to walking.

#### *4.5.3.1 Homolateral Creep and Crawl*

The data used to plot the results below was extracted from the image using the pause function on a home video (normally, home videos are 25 frames per second) then the data was loaded to Microsoft Excel for plotting and analysis. At first the child was told to creep homolaterally. The child started from rest and advanced his right elbow and right leg and then moved his left elbow along with his left leg. It was noted however, that as the left elbow and left leg were moved, his body did also move to come to a balanced position with the limbs. The cycle continued until the child reached the end of the sheet. Figure 4.11.

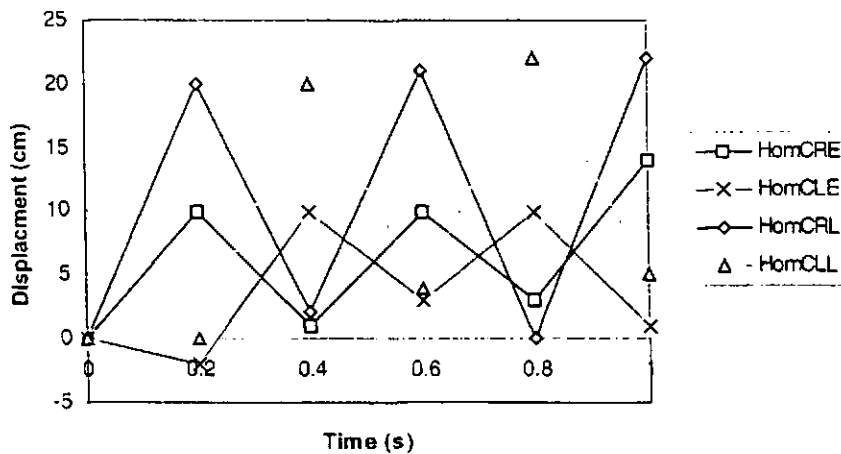


Fig. 4.11: Actual Homolateral Creep

As shown in Figure 4.12, each movement was measured from 'rest', i.e. when the child moved his right arm from point a to b, the stepping length was measured and point b was considered to be the starting point for the next move, i.e. from point b to c. The right and left elbows as well as right and left leg were monitored. Here the

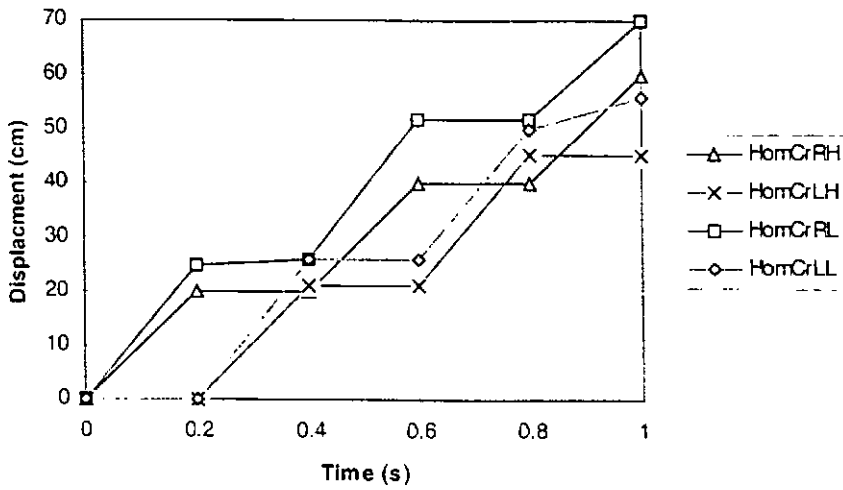
child was creeping homolaterally, as the right elbow (HomCRE) moved forward along with the right leg (HomCRL), the left elbow moved slightly backward, which was an indication that the child was using his left elbow (HomCLE) as well as his left leg (HomCLL) to push himself forward. Once the child reached a comfortable position, the left elbow and the left leg were pushed forward. In the interval just after 0.2 s to 0.75s the child felt comfortable and moved without any difficulties. Because the child was 2 m off the floor, this might have contributed to the fact the stepping distance was reduced, due to fear of falling.

Fig. 4.12: Actual Homolateral Creep of a healthy Child



In Figure 4.13, the cross crawl of the same child was analysed using the same video at a speed of 25 frames per second. But in this analysis the stepping lengths were accumulated, i.e. added up. It can be seen from the plot that the stepping distance of the child was not consistent, perhaps due to tiredness or lack of concentration. As the child progressed in crawling the stepping distance became bigger, which indicates that the child became comfortable with the method of homolateral crawling. As the child started the motion, right hand (HomCrRH) moved forward with the right leg (HomCrRL) and as soon as the child positioned himself, the left hand (HomCrLH) and left leg (HomCrLL) were moved forward. As shown below the stepping distances were within the range of 200 mm all the way through.

Fig. 4.13: Actual Homolateral Crawl



4.5.3.2 Cross Pattern Creep and Crawl

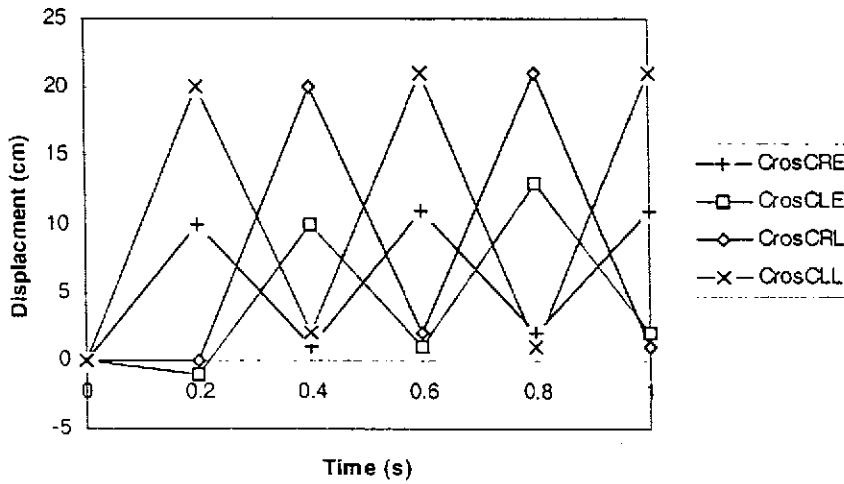
The same method of analysis was used again to extract data for the movements of the children in the cross pattern creep and crawl, as in 4.5.3.1.



Fig. 4.14: Actual Cross Pattern Crawl

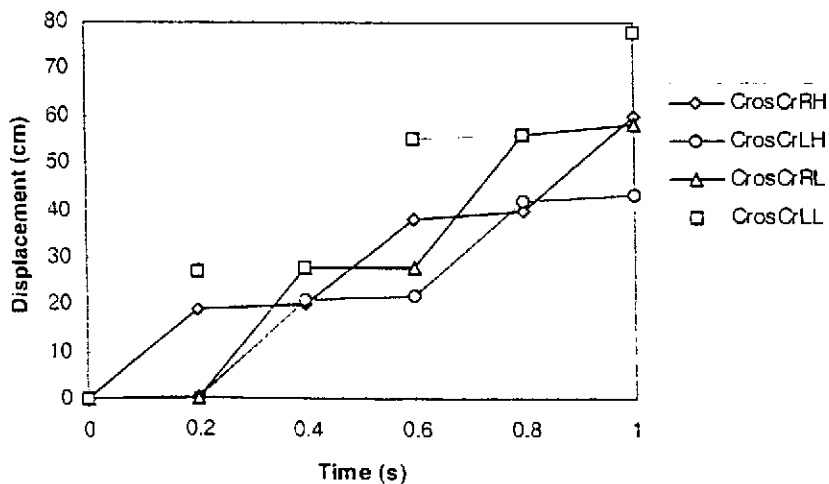
Here the movements, as shown in Figure 4.15, of the left (CrosCLE) and right elbows (CrosCRE) was consistent, with the left elbow having a slightly larger stepping distance than the right elbow.

Fig. 4.15: Actual Cross Creep of a healthy Child



This was because that particular child seemed to favour his left hand more at that stage. As the child progressed, the stepping distances became of equal magnitudes for both the left and the right elbows. The child moved both right (CrosCRE) and left legs (CrosCLE) with apparent ease and comfort. In Figure 4.16, the child movement

Fig.4.16: Actual Cross Pattern Crawl





was analysed by accumulating the stepping size distances. The child's legs, on average stepped up to 280 mm (starting from rest) without showing any signs of stress or fatigue. For both hands, the stepping length was within the range of 180 to 200 mm.

#### 4.5.3.3 Walking

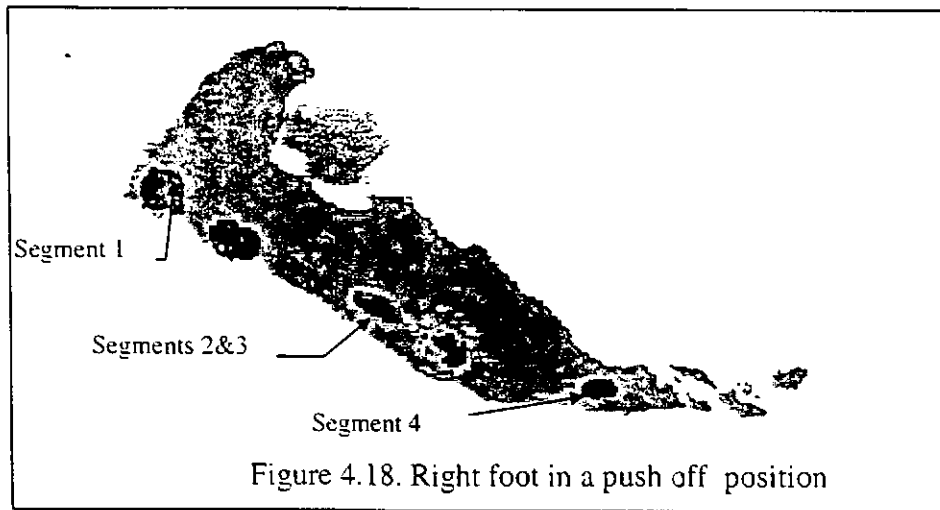
Walking is the most common means of moving from one place to another and is considered to be an essential part of every day life. Therefore by studying walking as shown in Figure 4.17, it became easier to understand other forms of locomotion such as crawling, creeping and running [Trew, 97]. It must also be noted that the speed of walking and the length of steps vary according to age and size, i.e. as the subject grows older the stepping length is reduced as well as the speed [Trew, 97]. Figure 4.18 shows an image of a foot that was captured using a high speed video camera at 200 frames per second, where the foot (right) was divided into four segments.



Fig. 4.17: Walking

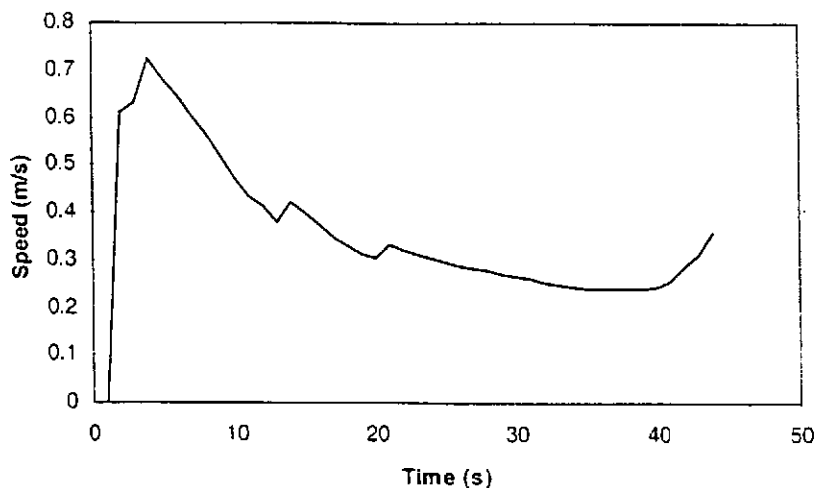
Segment 1 was at the heel, segments 2 and 3 were at equal distance in the middle of the right foot and segment 4 was at about the joint where the toes bend. An image analysis tool called Optimas (this instrument was available for only one hour, data listed in Appendix F) was used to analyse the movement of the foot where all designated positions were recorded. The velocity of the first segment of the moving foot was in the range of 0.36 m/sec, segments two and three were about 0.24 m/sec and segment 4 was approximately 0.21 m/s. The pattern of joint movement was

monitored at the ankle joints, since the hip has only one phase of extension and one phase of flexion, while the ankle has two phases.



In Figure 4.19, as the person started to walk, the heel rose at a speed of 0.6 m/s, and the heel reached a peak velocity of 0.72 m/s. Then the heel started descending and settled at an average speed of 0.36 m/s.

Fig. 4.19: Speed of Foot (segment 1, heel)



Figures 4.20 and 4.21 show the velocity - time relation for the middle two segments of the foot. The velocity of segment 2 was slightly higher than the velocity of segment

3. Segment 2 was at an average velocity of 0.24 m/s and segment 3 was at an average velocity of 0.21 m/s.

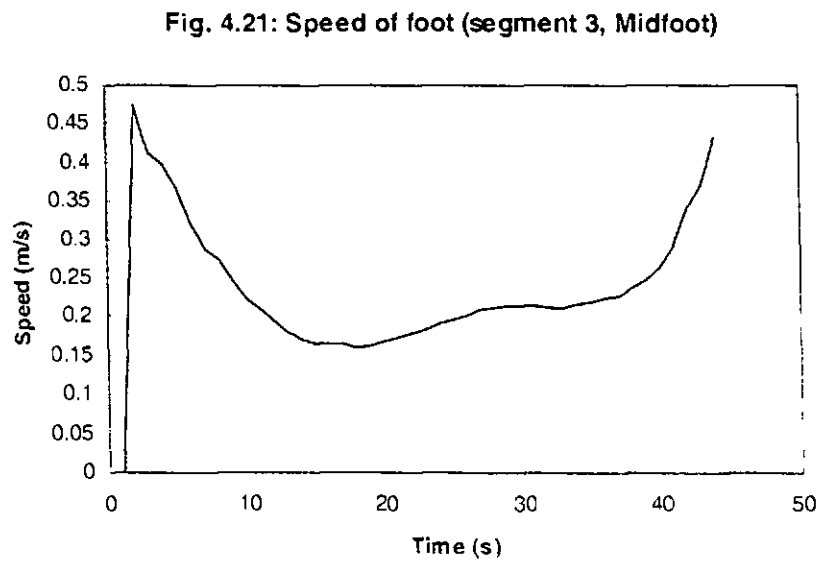
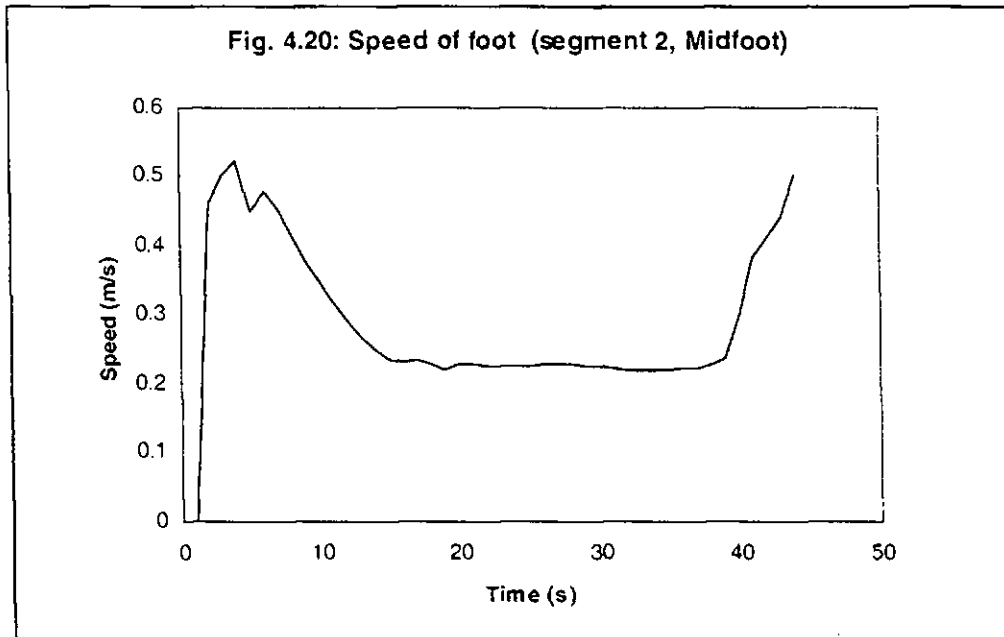
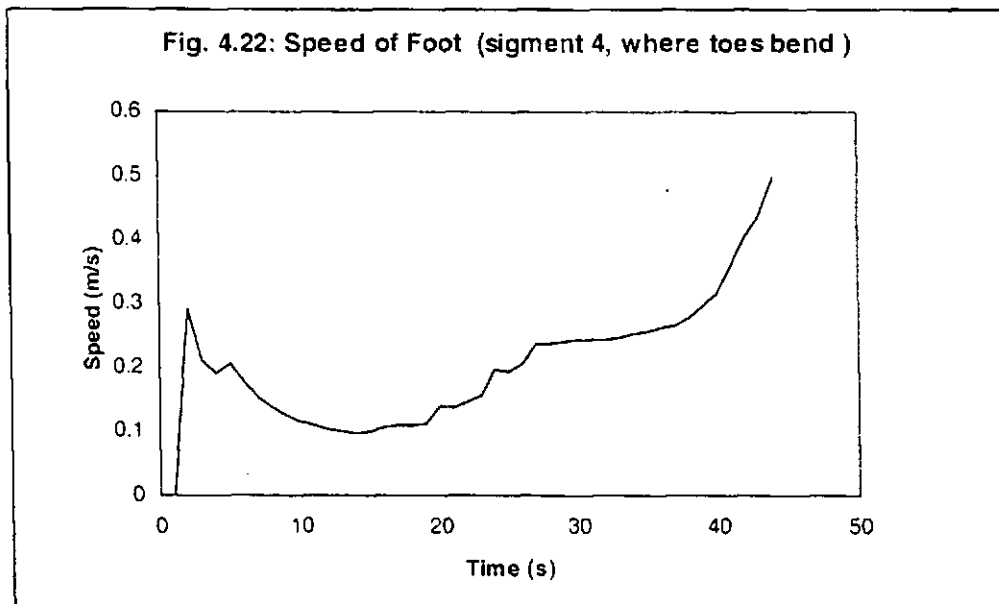


Figure 4.22 relates to segment 4 at the joint where the toes bend. Here the toes never left the floor until the other foot was fully on the floor. The toes velocity started with very low speed at 0.3 m/s and then fell to an average of 0.1 m/s, but as walking progressed the velocity picked up very quickly and reached its highest value when the subject lifted his foot off the floor to advance forward.



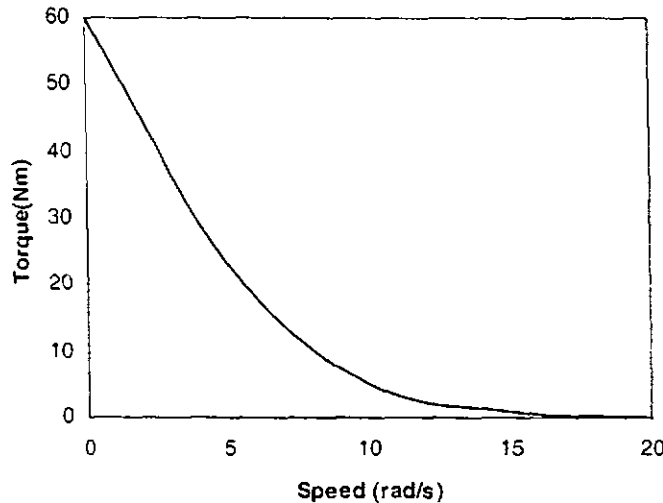
## 4.6 FORCE INTERACTION BETWEEN SYSTEM AND PATIENT

### 4.6.1 Introduction

After having considered the measurements of the human body and the dynamic measurements of the movements patterns, it was essential to consider the forces the patients might exert to resist the movement of the Patterner Machine. The forces developed by human muscles depend upon two factors: 1) muscle tension and 2) the mechanical advantage of the body's system, position and points where power is applied. Both of these factors change depending on the body's position and any external restrictions. The peak angular velocity of human shoulder joints is of the order of 2 rad/s, lasting for a period of 1s, while forearm rotation is two to three times faster than this and the peak rate of elbow movement is rather less than 17 rad/s and that of forearm rotation about twice as much [Martin, 72]. In this study, emphases are

put on the subject being in the prone position resisting the movement of a moving belt. A typical curve of torque against speed for an average elbow joint for an adult human male [McWilliam, 65], is shown in Figure 4.23.

Fig. 4.23: Torque/speed curve for average elbow joint

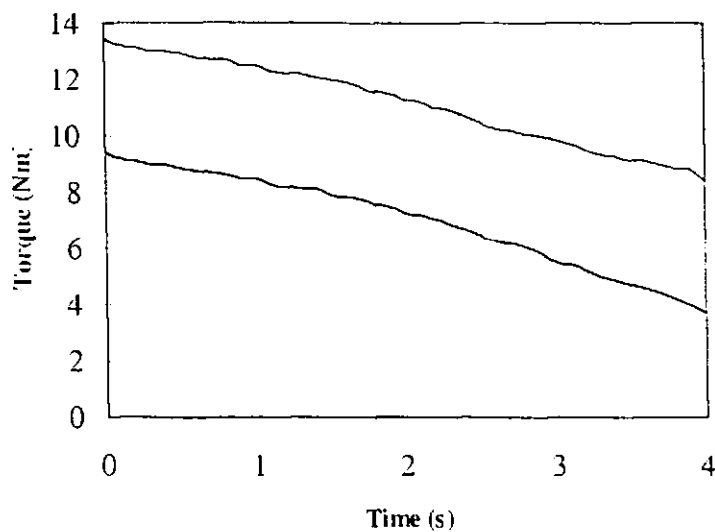


#### 4.6.2 Force Interaction

Figure 4.24 shows a simulation result using 3D Working Model (3D Working Model is a software that allows you to build a system of any specification, forces, torques, velocities and accelerations). The plot shows the torque required to operate the Patterner Machine. When two units of Patterner Machine were constructed and simulated, the results shown in Figure 4.24 indicate that the amount of torque needed to overcome the instant force exerted by the patient which is in the range of 130 N.

The simulation started with a huge spike in the torque plot at the onset, and the following was observed. The Patterner machine was initially at rest, and then the program exerted a torque that was necessary to attain the target angular velocity of 3 rad/s, in as few frames of simulation as possible. Consequently, the program initially exerted an exceedingly large torque to attain the angular velocity and to move the belt.

Fig. 4.24: Torque vs Time



Equation 4.11 is an alternative way of expressing the relationship obtained between force and velocity. This Equation describes the relationship between the force,  $F$ , exerted by the muscle on the load being moved and the velocity,  $V$ , of movement. As the speed increased the resisting force of the patient decreased [Fenn, 35].

$$F = F_{\max} [1 - (v/v_{\max}) / 1 + k (v/v_{\max})] \quad (4.11)$$

Where:

$$K = 5 \text{ (constant)}$$

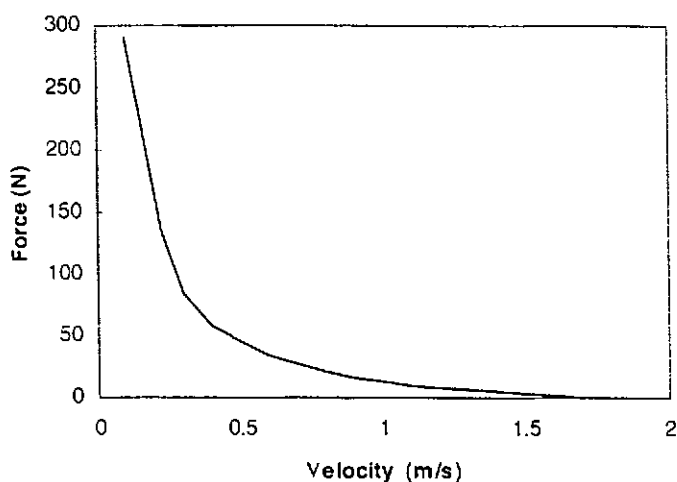
$$V_{\max} = 1.7 \text{ m/s (maximum velocity)}$$

$$F_{\max} = 111.2 \text{ N (maximum force a subject can pull in prone position)}$$

Equation 4.11, explains the relationship between force and velocity using the knowledge of human strength. It is well noted that endurance time falls rapidly as the muscle force requirement is increased [Kroemer, 1970]. Figure 4.25 shows the amount of time it takes the Patterner Machine to overcome the possible force the patient might exert to resist the movement of the machine. Here, it was noted that as the velocity increased the resistance of the patient decreased. At a speed of 0.5 m/s, the force exerted by the patient was 50 N, which is in fact the sustained force expected from the patient to maintain for a short time. By 1.5 m/s the force has decreased to as

low as 5 N. The plot shows that the force is zero after a velocity of 1.55 m/s, although this cannot be true in practice since each human limb has a weight.

Fig.4.25: Force of movement vs velocity



In order to ensure absolute safety for both the user and the operator, an investigation into the interaction between force limits was conducted to determine the instant and sustained forces the user might exert on the system. A strain gauge type force transducer was designed as shown in Figure 4.26, constructed and calibrated by the author with an accuracy of  $\pm 1\text{N}$  to measure the instant and sustained forces of humans in the prone position. The circuit was connected as a half bridge to measure the strain in terms of microinch/inch.

#### 4.6.2.1 Measurement of Instant and Sustained Forces

With the subject applying no force on the Strain Gauge Force Transducer (SGFT), the balance knob was turned to null. The subject applies the force, the meter deflects left. The larger knob is then rotated to the re-balance position until null is reached. The reading on the meter is then recorded. The re-balance of the knob can be rotated (in either direction) and that number of micro-strain from the noted reading represents full scale deflection. These readings were then converted to force measured in Newtons.

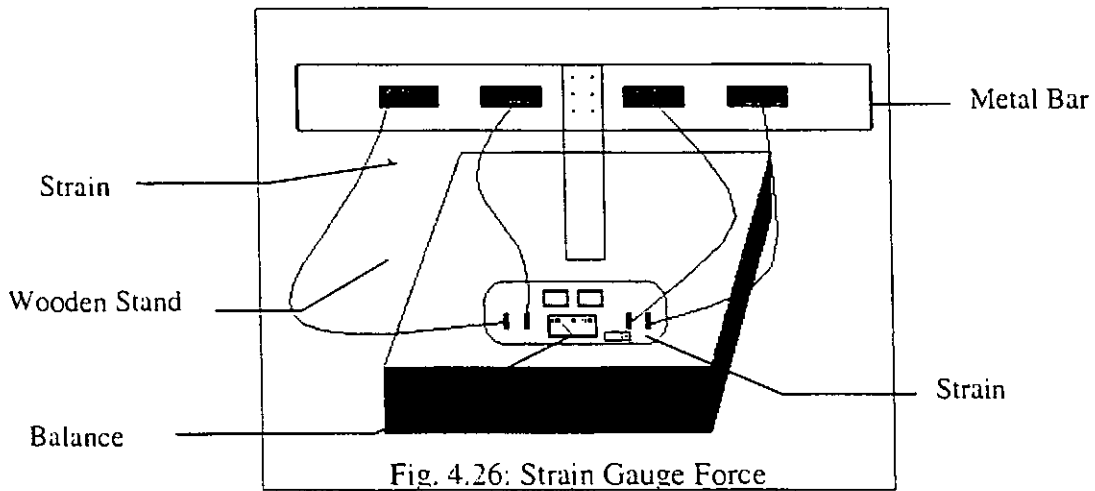


Fig. 4.26: Strain Gauge Force

The results of the conversion are shown in Figure 4.27. The experiment was divided into age groups according to the increase and decrease of force capability as the human subject grows up.

Fig: 4.27: Age vs Instant & Sustained Forces

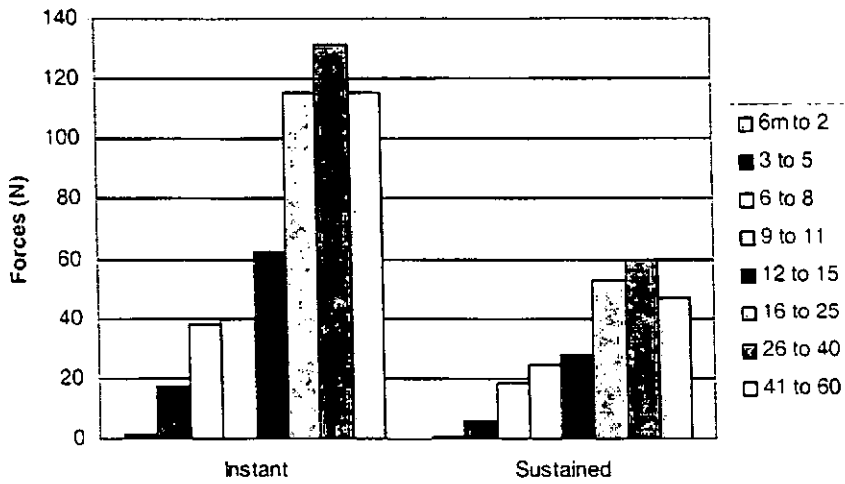
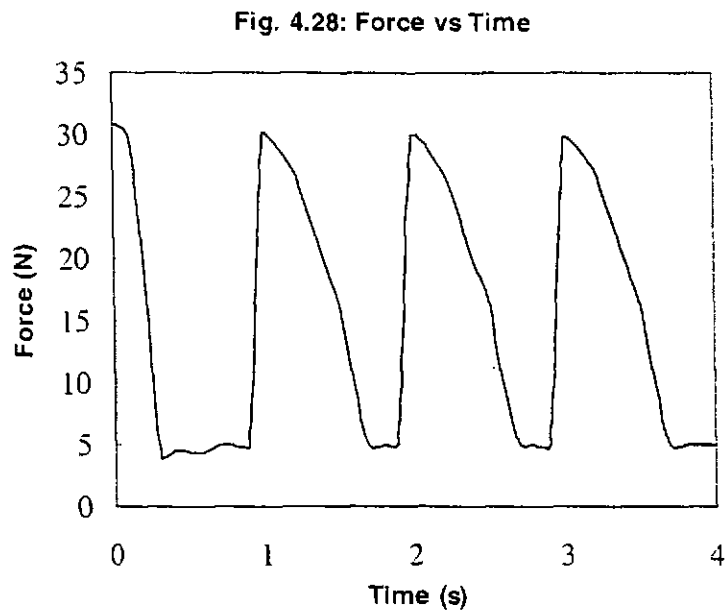


Figure 4.27 shows that age group 26 to 40 years old have exerted maximum instant and sustained forces whereas children of age group 6 months to 2 years exerted the least forces. As the subjects grow older (over 40 years old) instant and sustained force decrease slightly. Here the instant and sustained force shown are the total forces applied by the patient while laying in the prone position. Ignoring body contact with



the floor, it is safe to say, on the average, that each hand, for age group 26 to 40 years contributes 30 N of sustained force and 70 N of instant force.

Figure 4.28 shows the time it took the patient to lose strength through four cycles. Initially the patient resisted the moving machine and then applied force of the patient was reduced as the velocity of the belts increased. In the first cycle the sustained force was at about 5 N and the instant force was 31 N. In cycles 2, 3 and 4 the instant forces were reduced each time where as the sustained forces remained nearly the same.



## 4.7 SUMMARY

It was noted that the most common and the most flexible method of remedial treatment is the manual technique performed by humans. Human beings possess the qualities of adaptability and versatility which perhaps no mechanical system, no matter how sophisticated, can equal. Humans can perform the task of patterning without the requirements of being positioned accurately. Automation, however, often performs faster than people, for accurate repeated operations, which is a requirement

in this case. On the other hand, human beings also have less desirable characteristics. Machines do not suffer from fatigue or boredom, people do. Whereas worn bearings and belts can be replaced, emotional stress and fatigue is a cause for concern. People (intentionally or unintentionally) perform with a high degree of variability, whereas robots perform consistently (whether correctly or incorrectly).

It was essential to obtain accurate data concerning the measurements of limbs involved in the patterning process, such as arms, legs and body breadth for a wide range of humans. Muscle and strength for age groups under study was also considered as well as the effect of age (joint mobility decreases only slightly between age 20 and 60), gender (woman exceed men in the range of movement in all joints but the knee) and body built (slender men and women have the widest range of joint movements, obese ones the smallest). Dynamic human body dimensions obtained through this study have been an invaluable source of information upon which to base the design decisions. To a large extent this study has verified, updated and identified the needs of brain injured children. By involving parents and qualified occupational therapists in this project, every effort was made throughout this study to explore every angle possible to provide the parents of a brain injured child with the best patterning machine possible to perform the most difficult tasks which will help brain injured patients restore/enhance their mobility or recover fully as soon as possible.

Attempts were carried out to find a suitable design as was discussed earlier in this chapter, before the author decided to adopt the proposed design by Kavina and the concept of an endless belt. The two "preliminary" designs have conveyed a great deal of information that helped in formalising the final design. This also highlighted the need to measure humans in the patterning position. Mathematical expressions have also contributed in determining the step size and the degree of rotation of the limbs (without causing stress to the patients). The results obtained using high video cameras may not reflect the true performance of the patterning machine. On the patterning machine, the patient will be strapped to the platforms of the machine which may limit the patients' free movement. Therefore, to analyse the true functional performance of a patterning machine, a simulation model, to be discussed in details in Chapter \*\*\* was built accompanied by all the restrictive conditions used for patterning and the

effect of these factors, such as acceleration, speed, forces and resistance of movements exerted by the patient were analysed.

The design specifications for the mechatronic system were compiled once the most appropriate tasks which the mechatronic system is required to perform were identified. Analysis of most common forms of movement such as walking and other forms which are less common such creeping and crawling was carried out. The interaction of forces between the Patterner Machine and the user was fully investigated and then simulated. All the necessary arrangements were made with no compromise to system integrity. It was noted that the patient would lose the instant force to oppose the Patterner machine in movement within 0.025 seconds, but sustained force of 5 N is kept by the patient. The results of these investigations have led to the formulation of the design specification, which was the natural progression following all these analysis and investigations. The final design specifications is contained in Chapter 5.

# Chapter 5

## THE DESIGN SPECIFICATIONS

---

*My method is different. I don't rush into actual work. When I get a new idea, I start at once building it up in my imagination, and make improvements and operate the device in my mind. When I have gone as far as to embody everything in my invention, every possible improvement I can think of, and when I see no fault anywhere, I put into concrete form the final product of my brain.' Win Ng*

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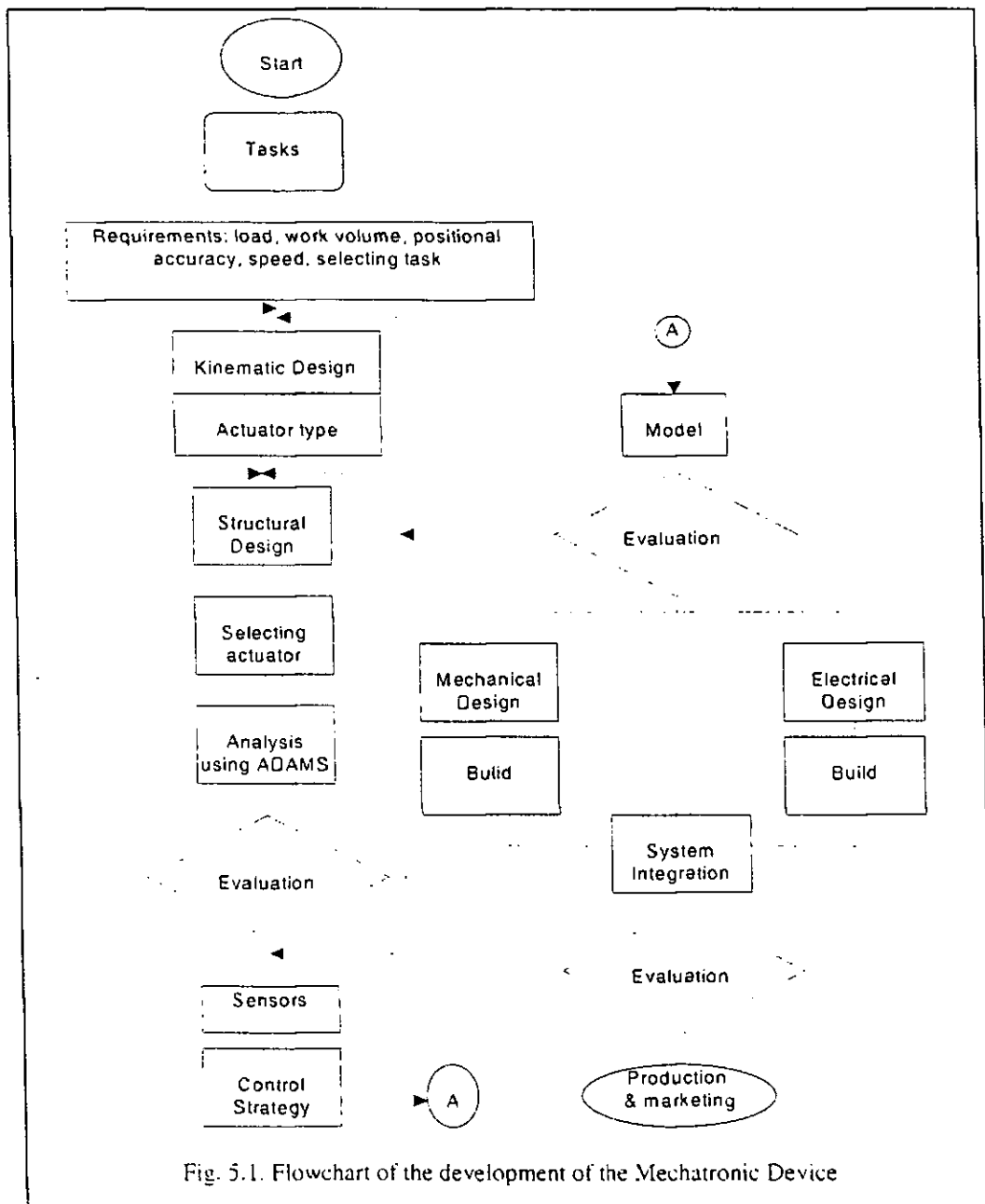
### 5.1 INTRODUCTION

Now that the task of the device has been defined and translated into performance requirements, the design process can begin. The design specification was the first step in the design process, whereby the most important tasks were translated into a form that could be accomplished. Since every kinematics design has a different selection of joint types and length of links that comprise the manipulator (unit), the choice of kinematics design is, in this case, the most important factor in the design. Therefore an integrated flowchart of the mechanical and electrical systems was constructed to cover the steps involved in the conceptual, preliminary and detailed design. The specification was the integral part of the design process, that had begun with the preliminary design specification before culminating in the final design specification. The final design specification is not necessarily the last specification to be written, as this may have to be changed during the modification / redesign phase of the project.

### 5.2 KINEMATIC DESIGN OF THE DEVICE

A flowchart for the mechatronic device was constructed to carry out the steps involved in the conceptual design, preliminary design and the detailed design. The kinematics arrangement of the patterning system determines to a large extent how

successful the design is going to be to accomplish the desired tasks set out by BIBIC. In determining the best kinematic arrangement many aspects of the user, operator and the brain injury institute were considered and the full list of the design criteria is listed in section 5.3.



Some of the patterning techniques have greater influences on the kinematic arrangement than others. i.e. cross pattern creep, but they are all important when determining the best kinematics design to pattern patients. The initial conceptual designs were discussed and the following as shown in Figure 5.3 is the final kinematic

arrangement that would perform the required tasks effectively and efficiently. Considering the measurements of the human body made in Chapter 4, these regarding the lengths of the upper and lower arm, upper and lower leg and breadth, it was decided that all units must be 100 mm wide to incorporate cross pattern creep and to subject the patient to the minimum stress practicable level of discomfort or stress particularly during cross patterning. In the first few input sessions of carrying out the patterning techniques, the subject may experience stress because of the stiffness of the patient's body. From the conducted surveys, measurements listed in Chapter 4, Tables 4.13 and 4.14 regarding the prone length for children and adults. Children prone length mean was  $1477.2 \text{ mm} \pm 5 \text{ mm}$  and adults prone length mean was  $2288.5 \text{ mm} \pm 5 \text{ mm}$ . Therefore it was decided that a suitable length of the units is to be 3 m from the centre of pulleys, in order to mimic actual creep and crawl. The majority of patients will be children aged 6 months to 13.5 years. It is necessary to provide a harness that will assist in the input and output sessions of the patterning process. During the input session the harness will be holding approximately 90 % of the patient's weight, leaving the patient just touching the moving units. In the output session, however, the units may support approximately 80 % of the patient's weight.

### 5.2.1 Final Design

After reviewing the designs available to date and after critically analysing the two preliminary designs discussed in Chapter 4, it was concluded that designing the proposed idea [Kavina, 96] is a realistic task. The objective is to mimic as closely as possible the actual creep and crawl a healthy child would normally experience, rather than to mechatronically mimic the actual Doman-DeLacato bench method.

The machine as shown in Figure 5.3 is the final design that would be expected to carry out the desired techniques prescribed by the British Institute for Brain Injured Children, BIBIC. The performance, the integrity and the implementation of this machine will be assessed in Chapters 6 and 7.

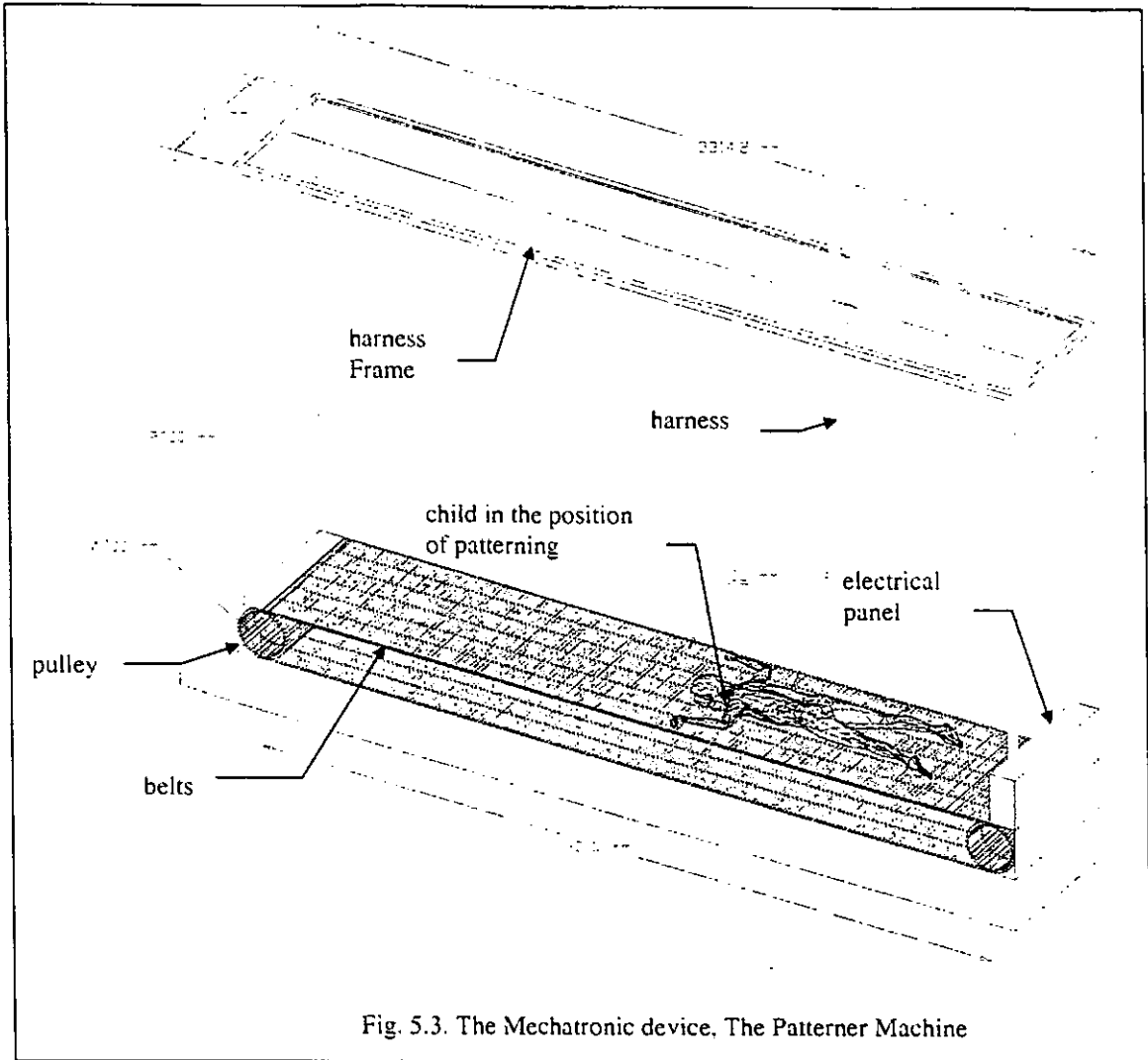


Fig. 5.3. The Mechatronic device, The Patterner Machine

## 5.3 DESIGN SPECIFICATIONS

### 5.3.1 Scope

This specification covers the preliminary designs requirements for a mechatronic device for use by brain injured patients. The specifications may change slightly when the remaining other five units are built.

### 5.3.2 Related Documents

- BİBIC development profile chart [Pennock, 91].

- Doman-Delacato exercising sheet [Doman, 60].
- Peto development chart [Scope, 94].
- Scope fact sheets [Scope, 94].
- Human body measurements [Doman, 66].
- Related books by BIBIC [Level 8, 93].
- Dynamic body measurements conducted by author.
- Actual movements and simulation results of human movements.
- Medical advises.
- Patent application by Kavina. 96 discussing the idea and the design concepts.

### **5.3.3 Terminology**

- The mechatronic system shall be referred to as the 'Patterning Machine'.
- Each conveyor belt module shall be referred to as a 'Unit'.
- The patient shall be referred to as the 'User'.
- The parent/helper shall be referred to as the 'Operator'.

### **5.3.4 General Requirements**

- The system shall be capable of use by the majority of brain injured (within the specified age range) supervised by any ordinary person (usually one of the parents).
- The operation of the system shall not require the use of any special skills although some self-training through the use of an instruction book, would be needed.
- The system shall be able to be used at home without any special modifications.
- The system shall be capable of being easily assembled/disassembled for ease of transportation, access and servicing.
- The user of the system shall not experience undue fatigue.



### 5.3.5 Design Requirements

- The system shall have the capability to perform homolateral and cross creep, homolateral and cross crawl and to walking.
- The system shall have an absolute positional accuracy of  $\pm 10$  mm.
- The system shall stop before reaching the specified end of the unit, reset all units and reverse back as one unit.
- The belt surface used by the patient shall not be higher than 500 mm from the floor.
- All units shall work as one system during operation.
- The system shall be designed to have a kinematics configuration which is stiff when the system is off.
- The system shall be designed to comply with any relevant British Standards Association Institute, BSI, and to be in full compliance with relevant safety procedures.
- The system shall be designed and programmed with reference to the top tasks listed in Section 4.5.

### 5.3.6 System Specifications and Dimensions

- The system consists of six belts. Each belt is 100 mm wide and 3000 mm long with respect to the centres of the pulleys, i.e. the pitch between pulleys for each unit is 3000 mm.
- The pulleys have a diameter of 200 mm each.
- The centre of the pulleys is connected to the frame at 400 mm above the floor.
- The system has a variable speed with 300 mm/s as its maximum speed.
- Frame dimensions are as listed in Appendix G.

### 5.3.7 Environmental Conditions

- The system shall be capable of operation within a temperature range of 0 - 50 ° C.
- The system shall be designed to prevent the ingress of dust and dirt.

- System noise levels are to be limited to 40 dB at 1 m since the patients will have a long exposure time. This can be achieved by shielding the motor as well as by the use of ear protectors when necessary.

### **5.3.8 Ergonomics and Aesthetics**

- The system's power supply shall come from the normal home mains source.
- The system shall be capable of continuous operation for at least 8 to 10 hours per day.
- The system shall be designed to conserve energy when static.
- The system shall be aesthetically designed in terms of form, colour and texture.

### **5.3.9 Safety**

- When in operation the system shall be prevented from causing injury to both the operator and patient.
- All external surfaces shall be free from sharp corners and projections.
- The system shall be mechanically stable at all times.

### **5.3.10 Cost**

- The system shall be designed to sell at a maximum retail price of £15,000 to £20,000.

### **5.3.11 Life Expectancy**

- The system shall not require maintenance for at least the first 1500 hours use, with an annual service and safety check up.
- The system shall have a minimum total life of at least 10,000 hours, about 6.8 years for a period of 4 hours per day.

## 5.4 SUMMARY

That detailed design specification was the result of the background search on the available patterning machines, the surveys conducted by the author, and experiments using high speed video equipment and image analysis. The design specification also included a requirement for both direct control and augmented control, which would enable memory locations to be saved and replaced. This would provide safety features such as position monitoring and control over the unit speeds.

The system is to be operated in the home environment, giving the patient efficient use, as well as freedom and convenience to the operator. It is also to be capable of a longer period of continuous daily use and have a long life span. It is extremely important to give the purchaser a competitive cost and high benefit to cost ratio, especially since the most likely purchasers of such a system would include a local health authority, a brain injury institute or the parents or carers of a brain injured patient.

# Chapter 6

## ANALYSIS AND IMPLEMENTATION OF THE MECHATRONIC SYSTEM

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*'Reason, then, primarily involves an analysis of discrete elements, inferentially (sequentially) linked; intuition involves a simultaneous perception of the whole. The word "rational" is derived from "ration," to break into segments. The common element in actions normally considered "intuitive" —a great insight, a superb dance movement, an immediate reaction in sports, an overall picture of a finished object or building design—is a simultaneity of perception'. Robert E. Ornstein, The Mind Field, Chapter 3*

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### 6.1 INTRODUCTION

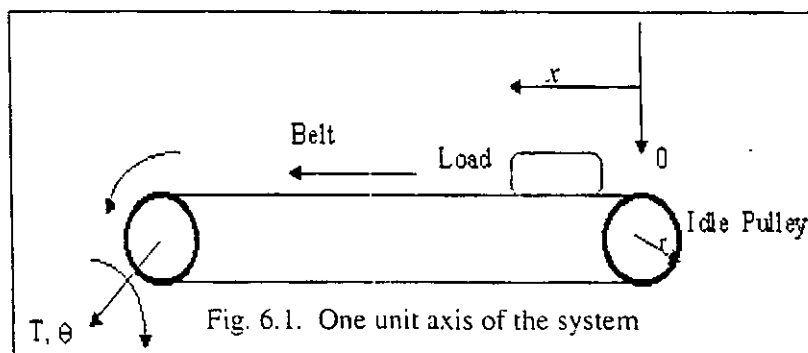
The aim of this research was to investigate novel design and construction aspects of a rehabilitation mechatronic device which can perform the tasks of patterning brain injured patients, especially children, at a cost the majority could afford. An investigation into a suitable kinematics arrangement was developed and a theoretical analysis of the performance of the system was given. An investigation of the most suitable actuator type and the best structural material was undertaken, as well as suitable methods of control. An overall assessment of the mechanical design decisions, such as type of material used to construct the frame, joint bearings and location of actuators was carried out.

## 6.2 THEORETICAL ANALYSIS OF THE SYSTEM

Below is the theoretical analysis of the system which describes the following objectives:

- A theoretical equation governing the performance of the system
- The efficiency of the current system
- Ways in which the performance can be improved

Each belt and pulley system employed in the final design effects rotary to linear motion conversion which is concerned with converting the rotational motion and torque from an actuator and producing a linear motion and force as the output. The transfer relationship of such a mechanical system is defined as presented in equation 6.1.



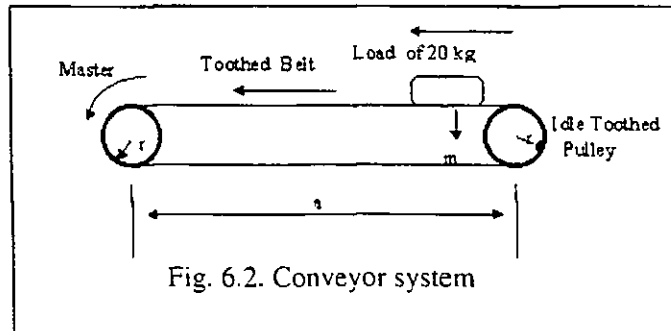
$$x = 2\pi r\theta \quad (6.1)$$

Here the linear distance travelled is proportional to the input, and the reflected inertia as seen by the input shaft can be shown to be as in equation 6.2.

$$J = Mr^2 \quad (6.2)$$

### 6.3 SYSTEM CALCULATIONS

The system will be using toothed belts which are commonly called timing belts, due to the fact that they do not slip, and hence have the ability to control specific movements with accuracy and safety.



Let the centre distance between the centres of the pulleys be 3000 mm. Figure 6.5. Hence, with ratio of pulley diameters of 1 : 1, with a diameter of 200 mm, then the total length of the belt,  $L_B$ , is 6628.32 mm, as shown below:-

$$L_B = 2a + \pi d_0$$

$$L_B = 2(3000) + \pi(200)$$

$$L_B = 6628.32 \text{ mm}$$

Assume a maximum velocity of,  $V_m = 0.3 \text{ m/s} = 300 \text{ mm/s}$ , (this comes from the normal walking speed of 18m/min) [Martin, 72], and a maximum mass of 20 kg (determined from the study) acting on each belt for a distance of 3000 mm in  $x$  seconds, reset for 0.1 second and then repeat. Then the acceleration of the system,  $a = V_m/t, 3000 \text{ mm/s}^2$ .

### 6.3.1 Calculation of the System Inertia

- *Inertia at Input Shaft:*

$$J_L = mr^2 = 20 (0.1)^2 = 0.2 \text{ kg m}^2$$

- *Inertia of Pulleys:*

$$I_1 = 1/32 \delta \pi D^4 W \text{ [Danfoss, 95]}$$

where  $\delta$  is the aluminum constant

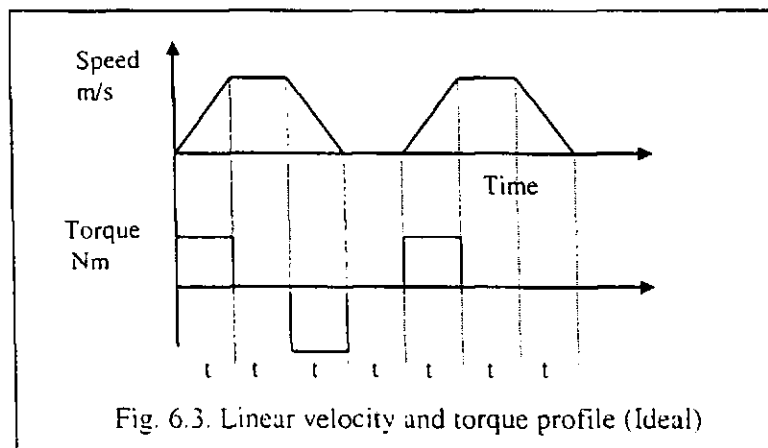
$$= 1/32 \times 2850 \pi \times 0.2^4 \times 0.125 = 0.11 \text{ kg m}^2$$

- *Mass of belt is equal to 5 kg*

$$I_2 = mr^2 = 5 (0.1)^2 = 0.05 \text{ kg m}^2$$

$\therefore$  the total inertia =  $0.36 \text{ kg m}^2$

### 6.3.2 Calculation of Torque



- *Torque to accelerate/decelerate:*

$$T_{\alpha} = J\alpha = 0.2 \times 30 = 6 \text{ Nm}$$

$$\omega_m = V_m/r = 0.3 / 0.1 = 3 \text{ rad/s}$$

$$\alpha = \omega_m / t = 3 / 0.1 = 30 \text{ rad/s}^2$$

- **RMS Torque:**

$$T_{rms} = \sqrt{\frac{\sum T^2 \cdot t}{\sum t}} \quad [\text{Infranor, 95}]$$

$$T_{rms} = \sqrt{2T^2 t / 4t} = 7.64 \text{ Nm}$$

### 6.3.3 Calculation of Power

- **Power at Shaft:**

$$P(\text{kW}) = \text{Torque (Nm)} \times \text{Speed (rev/min)} / 9550 \quad [\text{Stockline, 95}]$$

where 9550 is a constant, assuming a gear box efficiency of 0.58 as a worst case.

Then the power is:

$$P_s = 6 \text{ N.m (28.6 rev/min)} / 9.55 \times 10^3 = 18 \text{ W}$$

wher 28.6 rev/min is the actual rotating speed:  $N = 18 \text{ m/min} / (\pi \times 0.2)$

- **Input Power:**

As a worst case the efficiency of the gear box was considered to be 58 % and a service factor of 1.5 obtained from Stockline power, motion and control catalogue for uniform load that is running 2 to 8 hours per day and a number of starts of greater than 120 times a day. Then the total power per unit is:-

$$P = \text{power at shaft} \times \text{service factor} / \text{gear box efficiency}$$

Then the total input power =  $18 \times 1.5 / 0.58 = 47 \text{ W}$  for each unit.



## 6.4 IMPLEMENTATION OF PATTERNING MACHINE

There is more involved in the detailed mechanical design of a mechatronic system than mere decisions of simply selecting the bolts, brackets and bearings. Some factors that must be considered by the designer are: ease of manufacture which includes cost and ease of assembly, ease of installation, ease of modification and adaptability to specific tasks, ease of adjustment and calibration, ease of maintenance and availability of spare and replacement parts.

### 6.4.1 Mechanical Design Decisions

This design was guided by a number of decisions that were taken to make the design suitable for patterning brain injured persons without compromising the system integrity. Reasonable assumptions were made regarding the height, length, speed and spacing between the units of the Patterning Machine after consultation with the medical adviser team at BIBIC and some parents of brain injured children.

### 6.4.2 The Overall Mechanical Design

#### 6.4.2.1 *The Frame*

Two considerations were thought to be of great importance when designing the Patterning Machine structure (frame), these being strength and weight. An aluminium extrusion was chosen because it was lighter than mild steel and offered the strength required. The extrusion can be produced in different sectional profiles. Hollow aluminium square sections were preferred, to construct the frame, as compared with solid aluminium square sections, primarily for their reasonable cost and weight, which is about 40 % lower than the steel equivalent (Appendix G).

#### 6.4.2.2 *The Belt*

The power from the motor drives the timing pulley to a second timing pulley, and hence the toothed or timing belt. Timing belts have very important features of

preventing slip. Timing belts are preferred to lead screws and screw nut transmission systems, because they are cheaper, faster in operation and easier to install as well as being lighter and more compact. Other advantages of timing belts are that they can be used without lubrication and are silent in operation. The heat generated due to flexing is kept to a minimum because timing belts have a very thin cross section [Duggan, 1971].

#### ***6.4.2.3 The Bearings***

The main criteria that were taken into account when selecting a suitable set of bearings for the Patterning Machine are the need for quick assembling and disassembling of the unit since the machine is to be used mainly at the home of the patient, and the need for the bearings to offer the rollers an adequate support and still be as light as possible. There were a number of bearings on offer that can satisfy the set out conditions, such as Acetal bearings and Self-lube bearings. After analysing the information regarding these types of bearings, the designers opted to use Self-lube bearings with a four bolt flange which offers both the stability for the rollers and the compactness needed for the unit.

### **6.4.3 STRESS ANALYSIS OF THE STRUCTURE**

#### ***6.4.3.1 End Support of Roller Brackets (L Shaped)***

The actual mass of the belt is 4.3 kg with downward force of 42.2 N from the belt. The rollers exerted a force of 30 kN on the end support. Therefore the maximum deflection that can be exerted on the end support of roller brackets was 0.003 mm [Appendix G].

#### ***6.4.3.2 Support Shaft of Roller (steel bar)***

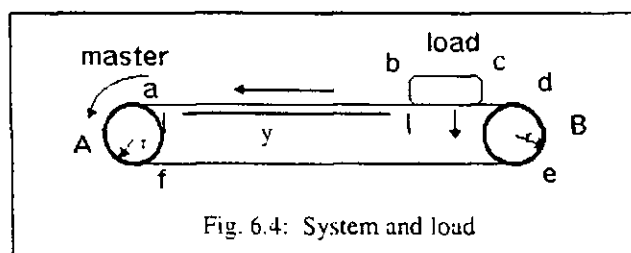
The load is evenly distributed on the shaft of 130 mm in length, the roller weights approximately 59 N. Then the maximum calculated deflection of the shaft supporting the roller was 0.002 mm [Appendix G].

## 6.5 SYSTEM TRANSFER FUNCTION

Toothed belts with self tracking rely on their teeth to grip the pulleys and are usually reinforced to prevent elastic stretch. Because of this, backlash is virtually eliminated where short belts are used. With the inclusion of a controller in the forward path and a feedback system, the closed-loop control system offers many more opportunities for parameter adjustment to obtain a desired response. An adequate model of the closed-loop transfer function was obtained.

### 6.5.1 Basic Mechanism

Here the action of the forces causes a reaction of the mass. This reaction is known as an inertia force. It represents the reluctance of a mass to change its velocity. The magnitude of the inertia force is mass  $\times$  acceleration of mass, that is  $Ma$ , and it acts in the opposite direction of  $F$ . In this system shown in Figure 6.5, pulley A is driven counter clockwise by a permanent magnet motor, section ab of the timing belt is in tension and transmits a force that will pull the load to the left.



- definitions:*
- |                          |  |
|--------------------------|--|
| 1) Load/ Slider dynamics | - from drive force to load position                  |
| 2) Drive system dynamics | - from motor torque to drive force                   |
| 3) Motor characteristics | - from input voltage or current to mechanical torque |

#### 6.5.1.1 Load Dynamics

Here the reaction to the applied force,  $F$ , is the inertia force  $Ma$ . Therefore these two forces plus the friction can be equated as

$$\text{Force (F)} = M a + \text{Friction} \quad (6.6)$$

Assume the sliding friction is negligibly small since the limbs of the patient will be strapped onto the belt. Referring to Figure 6.5, the traveling distance of the patient on the belt is given by:

$$y = a - b \quad (6.7)$$

*definitions:*

$l$  = effective length of belt ( $ab + bc + cd + ef$ ) = 3314.2 mm

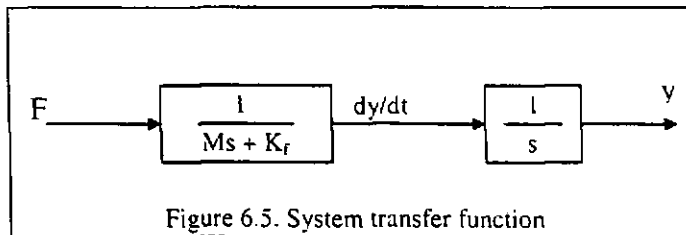
$M$  = Mass of limb

$K_f$  = Viscous friction coefficient of mass

$F$  = Force transmitted by timing belt

$$F = M d^2y/dt^2 + K_f dy/dt \quad (6.8)$$

then the equation of motion leads to the model shown in Figure 6.6



### 6.5.1.2 Drive Dynamics

Note here that the forces in the positive direction are positive because this is assumed to be the direction in which the acceleration is occurring, which is also the direction of positive velocity and acceleration. Since the timing belt is an elastic medium, then its behaviour can be summarised by one parameter -elasticity,  $K_e$ . Thus for a section of belt of length  $x$ , the actual elongation resulting from a tensile force,  $F$ , is given by:

$$\Delta x = F K_e x \quad (6.9)$$

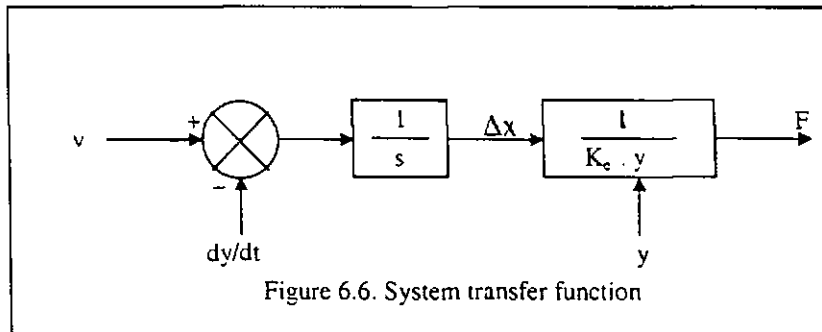
where  $K_e$  is the elasticity constant.

Alternatively force can be derived from stretch as:

$$F = l/K_e \Delta x/x \quad (6.10)$$

While the tension is uniform throughout that section of belt, the stretch between two points on the belt can in turn be obtained as the time integral of the difference between velocities of the belt at those two points. Assuming an anticlockwise turning, which makes  $F$  negative, then  $v$  is negative. Assuming also that  $x = y$ , where  $y$  is distance the patients travels on the belts, this yields leads to the following model:

$$\Delta x = \int (v - dy/dt) dt \quad (6.11)$$



Now a second aspect that should be considered is to derive the linear velocity,  $v$ , at the drive pulley from the motor torque. Here the inertia and friction associated with the pulleys and the motor must be taken into account.

*definitions:*

$R$  = radius of pulley in mm

$J$  = moment of inertia of pulley and motor rotor

$K_{im}$  = viscous friction coefficient of motor and pulley bearings

$\tau$  = mechanical torque developed by motor

$\omega$  = angular velocity of motor shaft

Consider the torque balance at the motor shaft. The forces opposing the motor are:

- Torque due to belt tension =  $FR$ , and
- Viscous friction torque =  $K_{fm} \omega$ .

Here the residual torque produces a shaft acceleration. Thus the equation of motion after substituting  $v = R\omega$ , becomes:

$$\therefore \tau = FR + K_{fm} \omega + Jd\omega/dt \tag{6.12}$$

This leads to the following model:

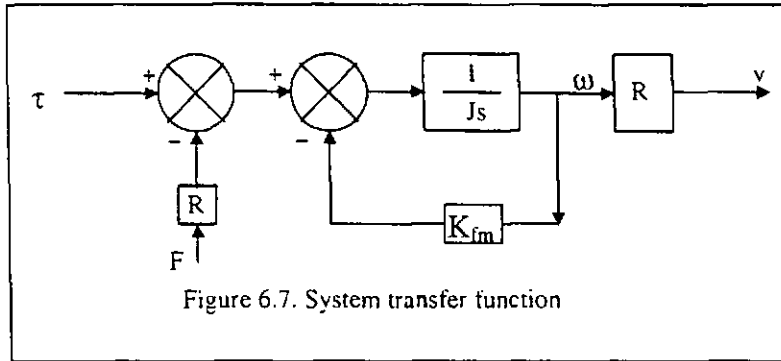


Figure 6.7. System transfer function

### 6.5.1.3 Motor Electrical Dynamics

Now consider a permanent magnet motor having a torque constant,  $K_m$ . Hence the torque resulting from an armature current,  $I$ , is:

$$\tau = K_m I \tag{6.13}$$

where  $K_m$  is the torque constant.

Then the armature back emf corresponding to an angular velocity,  $\omega$ , is

$$E = K_m \omega. \tag{6.14}$$

Thus the electrical model is shown in Figure 6.9.

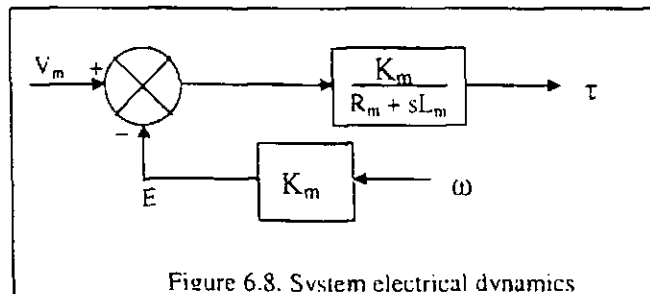


Figure 6.8. System electrical dynamics

Note that  $V_m$  is the voltage applied to the motor and the term  $(R_m + sL_m)$  is the armature circuit impedance. Note also that the electrical dynamic can be abstracted from the problem by employing a current drive (i.e. controlling  $I$ ) rather than a voltage one.

#### 6.5.1.4 The Complete Model

The complete model is an assemblage of these various sub-systems, Figures 6.5 to 6.9, resulting in a full transfer function of the system given in Figure 6.10. Despite the simplifications, the system contains a significant non-linearity due to the dependence of the gain term.

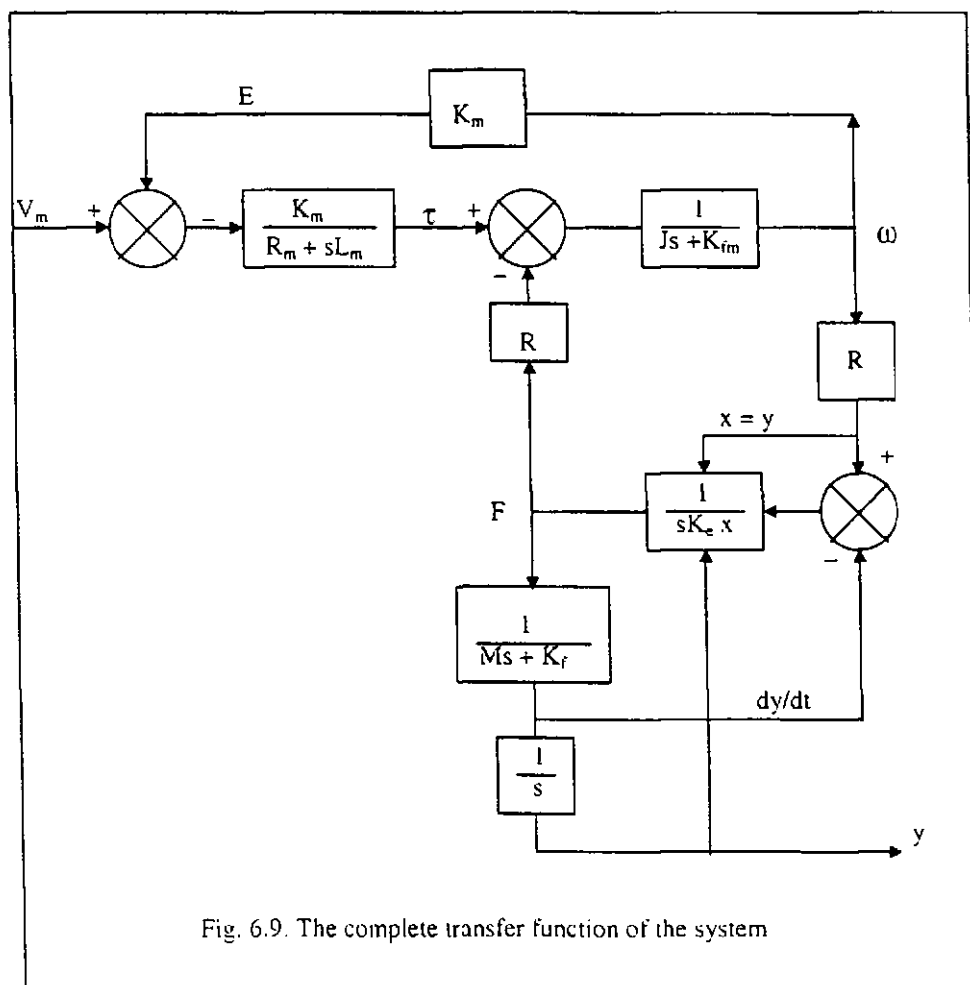


Fig. 6.9. The complete transfer function of the system

The transfer function shown in Figure 6.10 was used to control the motor which in turn controls the movement of the Patterner Machine.

## 6.6 FORMS OF DIRECT DRIVE ROTARY ACTUATION

### 6.6.1 Conventional Pneumatic and Hydraulic Actuators

Hydraulic and pneumatic actuators can also be used for robots and mechatronic systems. Hydraulic actuators are used in large, high performance, high cost robots: whereas pneumatic actuators are used more often in small, low performance low cost robots. Although, hydraulic actuators have the advantages of ruggedness and high safety factors, the disadvantages such as, cost, maintenance, noise, efficiency, fluid transport and flammability can outweigh the advantages[Andeen, 88].

Pneumatic actuators have advantages similar to those of hydraulic actuators in regard to ruggedness and safety in explosive environments. However, the load limitation is basically due to the pressure available from the source and it is usually 5 to 6 bar. This system is most suited for light loads at high speed with low cost. Another advantage that pneumatic actuation offers, is that such low-cost actuation methods for linear motions, and the components used, are relatively cheap and easy to maintain.

As a result of the compressibility of air, pneumatic actuators are not very stiff and have a relatively slow response (compared to hydraulic or electrical actuators). Therefore, pneumatic actuators are not well suited to use in high performance servo control applications. One other important factor is safety and in this respect electric and hydraulic drives generally tend to be safer than pneumatic. Electricity and air are clean and although hydraulic systems tend to be messy, oil is virtually incompressible and no explosive problems should occur. Purely pneumatic components may however be preferred in a fire hazard area when either electric or hydraulic drives would be potential risks [Fraser, 94].

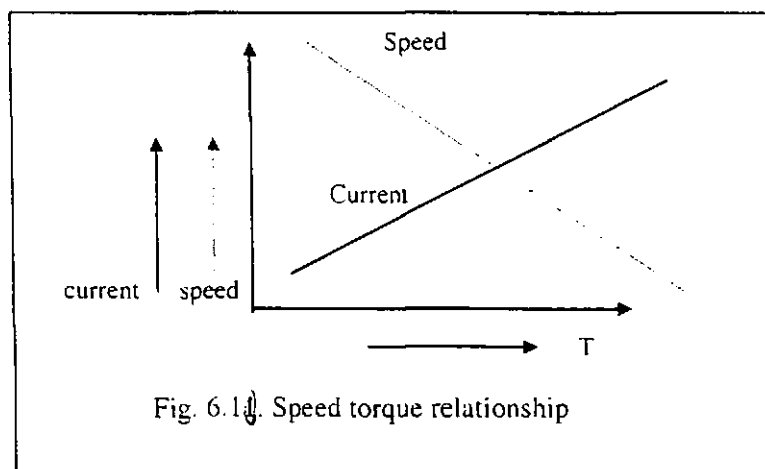


## 6.6.2 Conventional Electrical Rotary Actuators

Several types of electric motor are available. Each of these motors can be configured for linear or rotary motion. Rotary motors are currently far more popular for robotics applications, but more applications of linear motors may occur in the future. All rotating motors consist essentially of a stator, a rotor and some windings. When the electric motor is switched on the rotor rotates continuously until the power is switched off again. Stepping motor action differs from this because, even when the motor is switched on, the shaft remains stationary until a step pulse is sent to the motor [Fraser, 94].

### 6.6.2.1 Permanent Magnet Motors

The principal variation among different types of DC motors lies in the mechanism used to develop the magnetic field. In this type of motor, the field is developed by a permanent magnet which eliminates the wound field and substitutes a powerful permanent magnet to produce a magnetic field. The PM motor consists of an annular brush ring assembly, a permanent magnet stator ring and a laminated wound rotor. PM motors are suitable where size, weight, power and response times must be minimised and high positional accuracy are required. Commercial permanent magnet motors are available in different sizes, ranging from 35 Nm at about 25 mm diameter to 13.5 Nm at about 3 m diameter. The speed / torque curve for a permanent magnet motor as shown in Figure 6.11 is linear. As the speed of the motor decreases, the torque continues to increase as shown below, but increases directly with the input current, independently of the speed or angular position.



### 6.6.2.2 Stepper Motors

A stepper motor is a device that converts a DC voltage pulse train into a proportional mechanical rotation of its shaft. The speed may be varied by altering the rate of the pulse train input. Stepper motors are unique because the motion of the rotor is precisely determined by the input signals to the motor. Because of the fixed relationship between the rotor motion and input signals, stepper motors do not require an encoder and servo control system in order to achieve the precise positioning required in mechatronic and robotics applications.

However, depending on the particular stepper used and the inertia characteristics of the load, there may be certain motor speeds where a resonance phenomenon can occur. The motor may miss steps or make extra, undesired steps when operating near this resonance speed. During the application of each sequential pulse, the rotor of a stepper motor accelerates rapidly towards the desired position. Upon reaching the new position there will be some over shoot and oscillations unless sufficient retarding torque is provided to prevent this happening. These oscillations can cause resonance at certain pulse frequencies resulting in a loss of torque. Moreover, owing to inertia the motor may also lose steps, if subjected to excessive acceleration and deceleration.

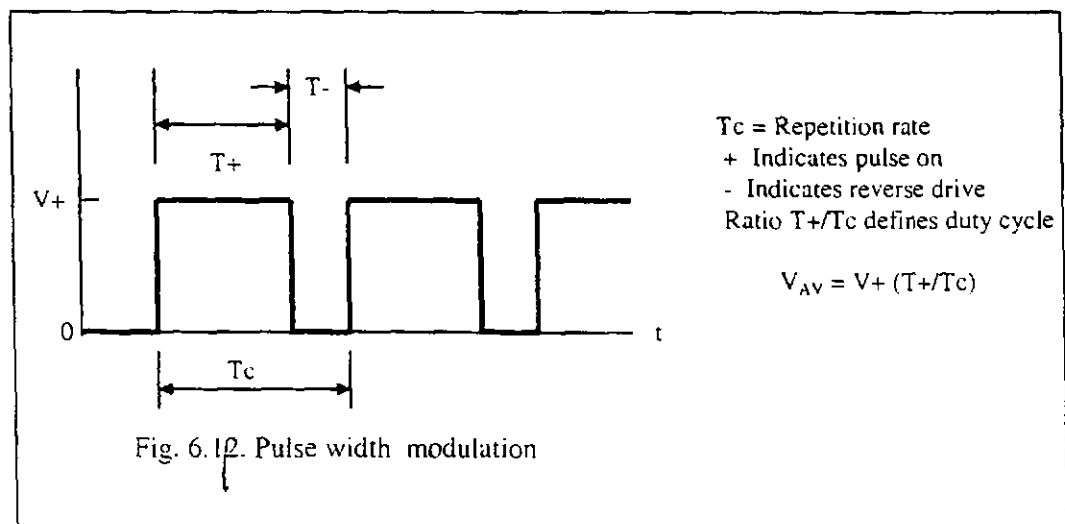
Since no feedback is required, this type of motor is found in a great number of applications, particularly in printers and plotters. However, in robotics and mechatronic applications, stepper motors have found less applications. This lack of feedback is both the greatest attribute and the greatest drawback of this type of motor. On the one hand, it provides exceptional simplicity of interface and control, but the range of applications where this control is suitable is quite limited. More sophisticated feedback strategies may be used with stepper motors, but even if used, stepper motors can only provide a lower power to weight ratio than a comparable DC motor. In this research program if stepper motors were to be used, they would require a controller of comparable complexity to ensure safety for the patient.

## 6.7 METHODS OF MOTOR CONTROL

Any mechatronic system, such as a robot or a patterning machine, needs a number of actuators, which may act dependently or independently of each other. The motors can be controlled via some supervisory system, such as a dedicated computer, a control circuit interfaced to a computer or a key pad. For independent control of more than one motor the controlling system must be able to control all motors concurrently and accurately.

### 6.7.1 Pulse Width Modulation (PWM)

Instead of driving the DC motor with a constant voltage or current, the motor can be driven, through suitable electronics, by a rapidly changing current. This method involves supplying the controller with a stream of pulses. The frequency determines the position of the motor shaft, and the rate of change of frequency determines the speed at which the motor should move in the desired direction. The control range can be achieved by switching power to the load for variable time intervals at a fixed frequency. Such control technique can be applied using either software via the port or programmable oscillators.



The principle advantage of PWM over linear control is the simplicity of the drive electronics and the ease of computer interfacing. However, there are some limitations

when using PWM control. The motor is continually switched on and off due to the pulse nature of the system, which makes the motor draw excessive current and introduces a lot of electrical noise due to the rapid switching of current through the armature [Snyder, 85]. This RF noise has to be filtered from the rest of the control logic [Shoham, 84]. Due to the construction there will always be a small error signal present on the motor, causing the motor to hunt or oscillate continuously. This can be removed with more control circuitry but at extra cost and complexity. Generally, for the purpose of this project, PWM provided the quickest and easiest mechanism for attaining proportional and derivative control of the permanent magnet DC motor. One of the main concerns that was raised regarding the use of PWM was will the speed go down to zero when one of the limbs is stationary while the other limb is being patterned. Since PWM uses transistors as on-off switches and the output voltage is a constant frequency and fixed amplitude waveform whose duty cycle is smoothly varied with input voltage, then at zero input the output is switching back and forth between the positive and negative power supply voltages, and this voltage appears across the motor armature. However, little armature current flows, because the armature time constant is too long relative to the switching frequency. The average current and thus the motor torque is exactly zero, so the motor stands still. A positive input voltage, however, increases the duration of the positive portion of the cycle and decreases the duration of the negative portion by an equal amount. Now the asymmetrical square wave has a non-zero average voltage that produces a proportional current and torque, causing the motor to rotate.

### **6.7.2 Pulse Position Modulation (PPM)**

Pulse position modulation is very similar to PWM. It differs in that several position signals can occupy the same wire. The position information is a function of time, but instead of a change in frequency that leads to a change in position, PWM uses time separation of each of the pulses to indicate the position. Its drawback is the fact that it is only used in small applications where only one channel of information is needed.

### 6.7.3 DC Control

This method of control is easy to implement and has less noise than PWM. It operates by encoding position information which involves sending a DC analogue voltage to the controller, this voltage is directly proportional to the position required. A sensor mounted on the motor provides the position information for the controller to turn into another DC voltage. These two voltages produce an error which is 'the error' used to adjust the motor position. The binary value held by the counter is converted into an analogue signal by a DA converter to be compared with the position request from the computer. This method of control can be affected by noise, the problem being solved by screening and by using a simple decoupling capacitor. Although it is possible to achieve direct control of the torque with the simple addition of a sense resistor and an operational amplifier to a push-pull circuit, it is thought that for this kind of application the motor should preferably be driven by a rapidly changing current.

### 6.7.4 Binary Encoding

This method is similar to the DC control method except without the two DA converters. The position request is in the form of binary numbers, which are then compared with the value held in the counter and any difference used for the error signal to a motor drive. This method is not suited for this application, as each axis would require at least 16 wires, i.e., two computer ports. Another disadvantage is that without a local processor the comparison of the request and position numbers would have to be carried out with a larger number of logic devices which would add more to complexity of the system as well as the cost.

## 6.8 SUMMARY

For the purpose of this project, it was decided to use permanent magnet DC motors for their high stall torque, small frame size, the linearity of the speed torque curve and their lesser requirements for cooling. The result of investigating into the methods of providing positional feedback of the motor, revealed that pulse width modulation (PWM) is suited, although the motor can also be driven with a constant current. PWM

may be used because of the simplicity of the drive electronics over linear control and for the ease of computer interfacing since only two output bits are required which outweigh its disadvantages.

The realisation stages of the project have enabled the kinematic design of the mechatronic device to be integrated with the most suitable actuators and methods of motor control. The prototype shall incorporate all the design specifications listed in Chapter 5 with slight modifications when necessary.

# Chapter 7

## SIMULATION RESULTS

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*'There are two ways of constructing a software design. One way is to make it so simple that there are obviously no deficiencies. And the other way is to make it so complicated that there are no obvious deficiencies.'* C.A.R Hoare, c 1980.

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### 7.1 INTRODUCTION

Although the human body is flexible, it has its limitations and therefore any designed medical engineering system must work within these limitations. Biological and biomechanical aspects such as the range, strength and speed of human movements, as well as body composition and response to physical phenomena such as acceleration and vibration, need to be carefully considered in any medical engineering design. Such relevant biomechanics aspects were studied amongst small groups of nursery school and elementary school children in the London area, and also amongst brain injured children at BIBIC. All biomechanical measurements were obtained under the conditions relevant to the patterning techniques under investigation, e.g. the prone position, in respect of the placement of the user, and of forces exerted by or on the user, with emphasis on safety as well as an optimal control strategy.

### 7.2 Simulation Results

Upon studying the development profile sheet, specially designed by BIBIC, it was noted and concluded that the most important tasks that were required for patterning brain injured patients are: 1) homolateral creep and crawl, 2) cross pattern creep and crawl and 3) walking. Homolateral creep requires four units or belt modules of the Patterner Machine, whereas cross pattern creep requires six units or modules.

Homolateral and cross pattern crawl require four units whereas walking requires only two units.

### 7.2.1 ADAMS Results

A computer model of the kinematic arrangement was created using ADAMS/View. The model was built to scale and the part builder was used to create the geometric elements needed for the belt and the pulleys. Mass and inertia properties were also considered. After creating all the necessary constraints and joints the model was verified. The system then was analysed and animated and the results of the animation are shown below in Figures 7.1 to 7.4. These Figures represent the performance of a single unit of the Patterner Machine with regard to the displacement over three segments, the velocity and the acceleration of the machine.

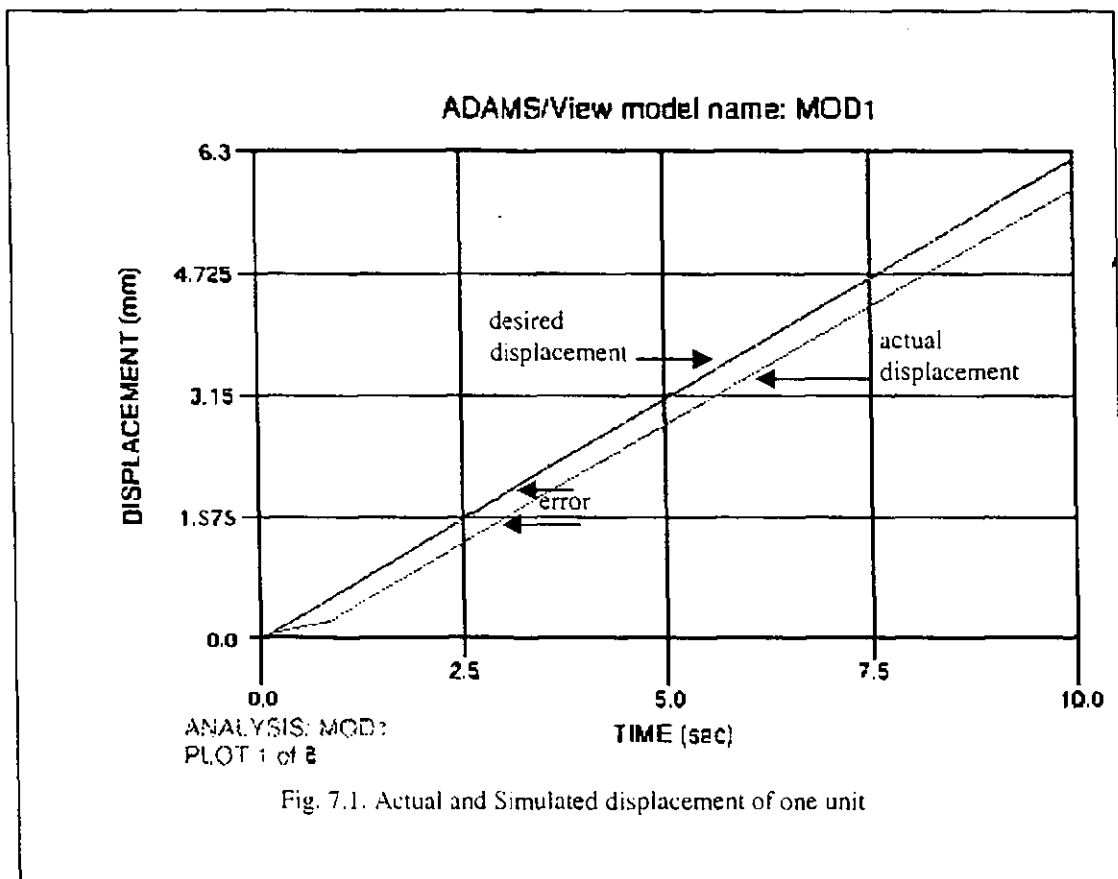
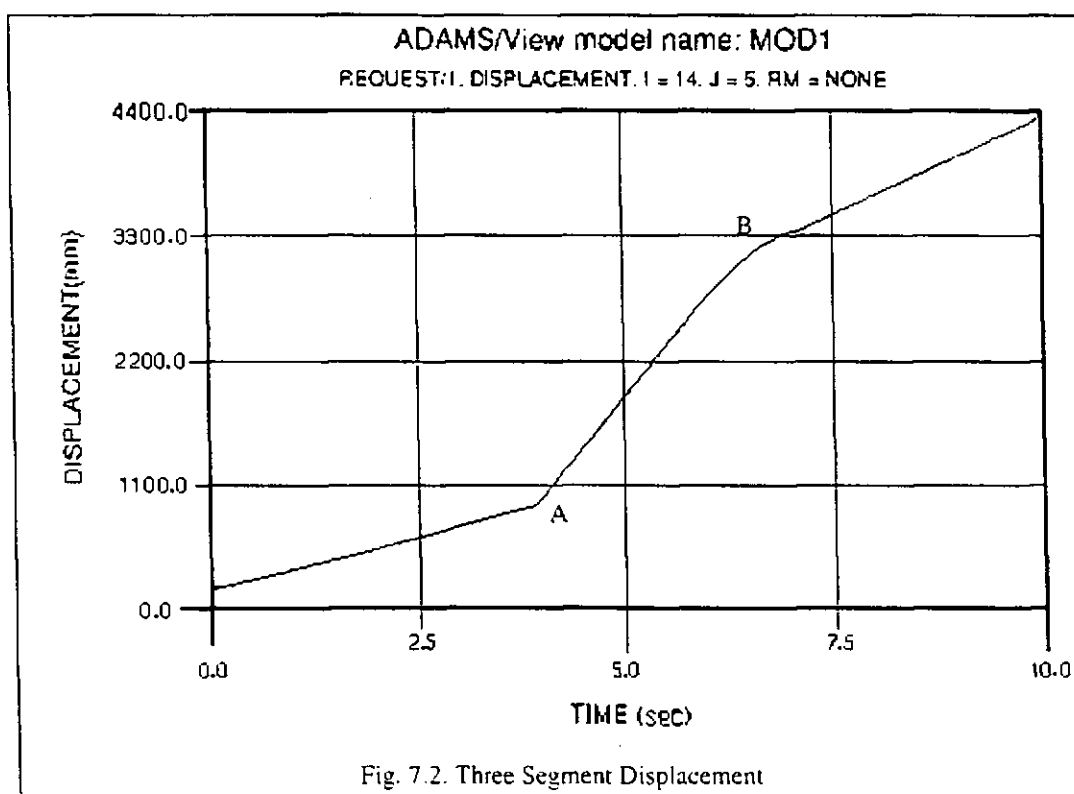


Fig. 7.1. Actual and Simulated displacement of one unit

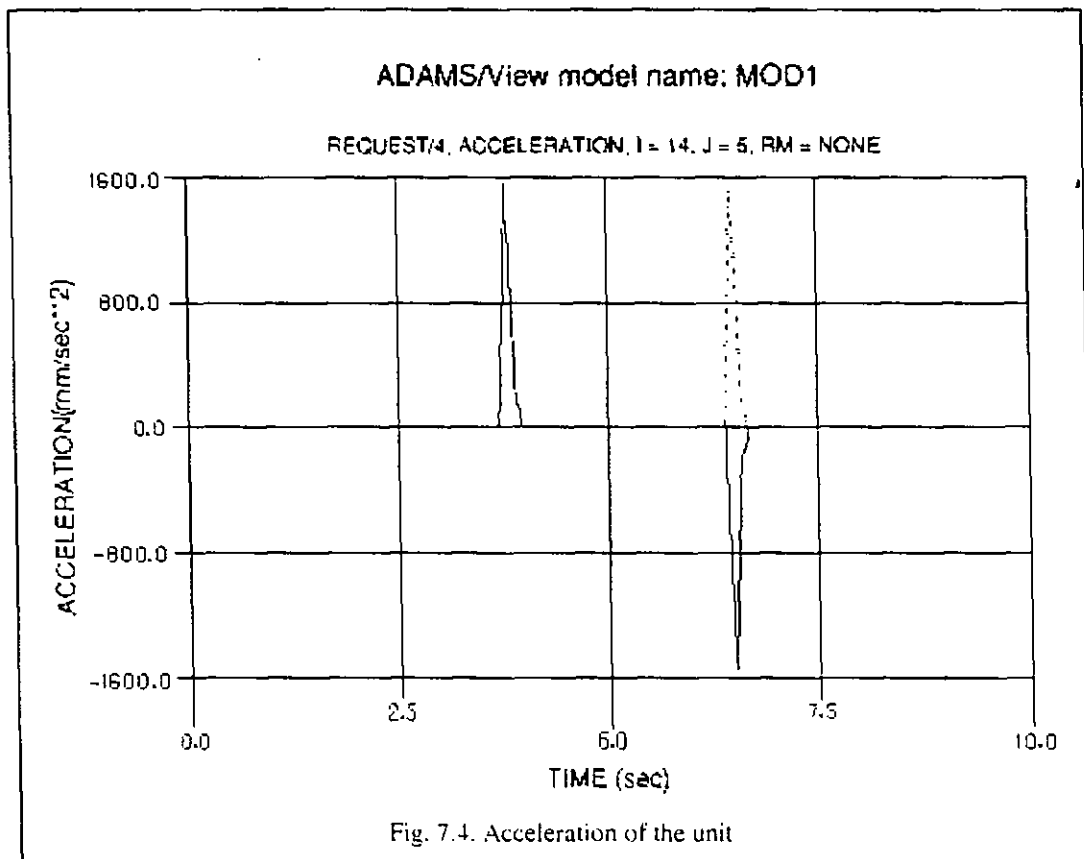
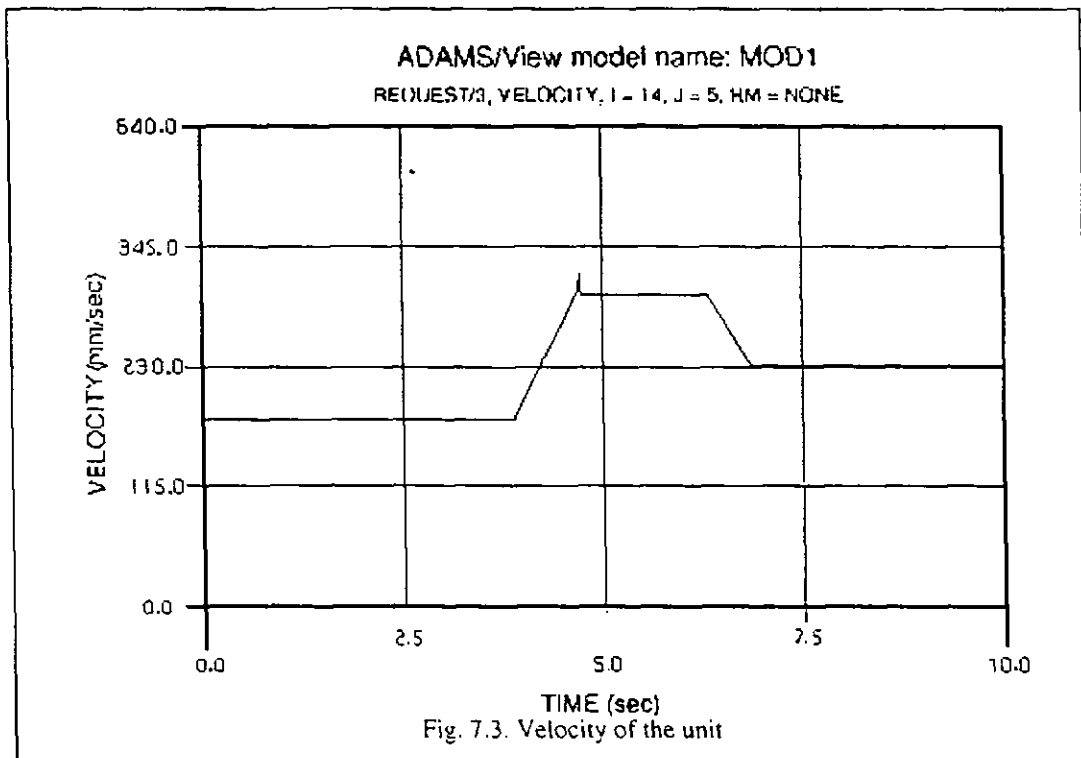
In Figure 7.1, the machine started from rest and travelled along at a constant speed. The mode at which the unit travelled was a stop and go. i.e. the belt moves a specified period then pauses then moves again. The displacement plotted against time showed a



ramp function where the actual displacement lagged slightly, due to the time (damping effect) needed to respond to the input signal. Damping resulted when introducing friction at the output. Figure 7.2, shows the displacement of the belt at three different speeds (stop and go). The load started to move from rest with an initial velocity of 0.0 m/s and was made to reach a maximum (final) velocity of 0.30 m/s with an acceleration of  $3 \text{ m/s}^2$ . The first displacement reached its desired destination at point A at 850 mm at a time segment of 3.75 seconds. Then the machine started the second segment to reach point B at final velocity of 0.79 m/s., at a time of 6.88 seconds. The total remaining distance, segment three reached the final destination with a velocity of 0.26 m/s.



Figures 7.3 and 7.4 show the velocity and the acceleration of the Patterner machine system under ideal conditions, where friction was negligible. The machine started from rest 'segment 1' at 0 velocity and then it ramped to a final velocity of 0.3 m/s to



reach point A, which the start of the second segment. The velocity in the first segment was 0.26 m/s. In the second segment the machine was set to travel at 0.79 m/s to

reach point B as soon as possible with an acceleration of  $1.5 \text{ m/s}^2$ . The third segment the system velocity ramped down to  $0.26 \text{ m/s}$  associated with a decrease in acceleration. It can be noted that the machine ramped into the third segment smoothly with the same speed as in the first segment, which indicates a smooth transition but at point A when the speed was very high with regard to the purpose of patterning the transition from segment 1 to segment 2 was not as smooth as the transition from segment 2 to segment 3. Therefore for effective patterning the speed of the Patterner Machine should be set to constant value before starting the patterning techniques and the speed of the machine should not exceed  $0.3 \text{ m/s}$  which is the walking speed for an adult normal human being.

### 7.3 SYSTEM CONFIGURATION

This device can use both linear and rotary actuators. After careful consideration of factors such as performance, and cost, rotary actuators were selected as being best suited to the research programme. Figure 7.5 shows how the system is interfaced to a Personal Computer (PC-386) data acquisition system, which was used to store and recall data entered by the operator. The detailed schematic diagram which includes all relevant connections between the motor, drive, encoder, controller and computer, is shown in appendix C. A suitable motor (the one used for the prototype) is the 3633-3Y precision permanent magnet DC motor fitted with a reduction of ratio of 30:1 gearbox, a standard encoder of 1000 count line, i.e. 1000 divisions per revolution of the motor. The drive used was the BRU 100 high performance dynamic velocity controller providing a modified 'S' shaped velocity profile, as in Figure 7.8. The signal drive was for a three phase permanent magnet brushless motor with hall effect commutation sensing. It was provided with a forward current of  $15 \text{ mA}$ . this system carried its own low voltage power supply, a DC Bus generation, a regenerative dump and an input/output. Extensive protections were incorporated into the drives including current foldback which meant to reduce the current to a safe level if the continuous rating was exceeded. A transformer was needed in order to provide the BRU 100 drive with a medium voltage AC supply which was rectified to produce the DC power Bus. An internal switching regulator generated low voltage supplies for the

logic, encoder, halls and an I/O supply. The permanent magnet DC motor (PM) was driven by a switching waveform at a nominal frequency of 500 Hz from a single bit on the microcomputer's port. The motor's speed was varied using pulse width modulation.

For convenience purposes a special key pad will be used with the final version of the system, which will consist of very simple commands that any ordinary person can use with ease.

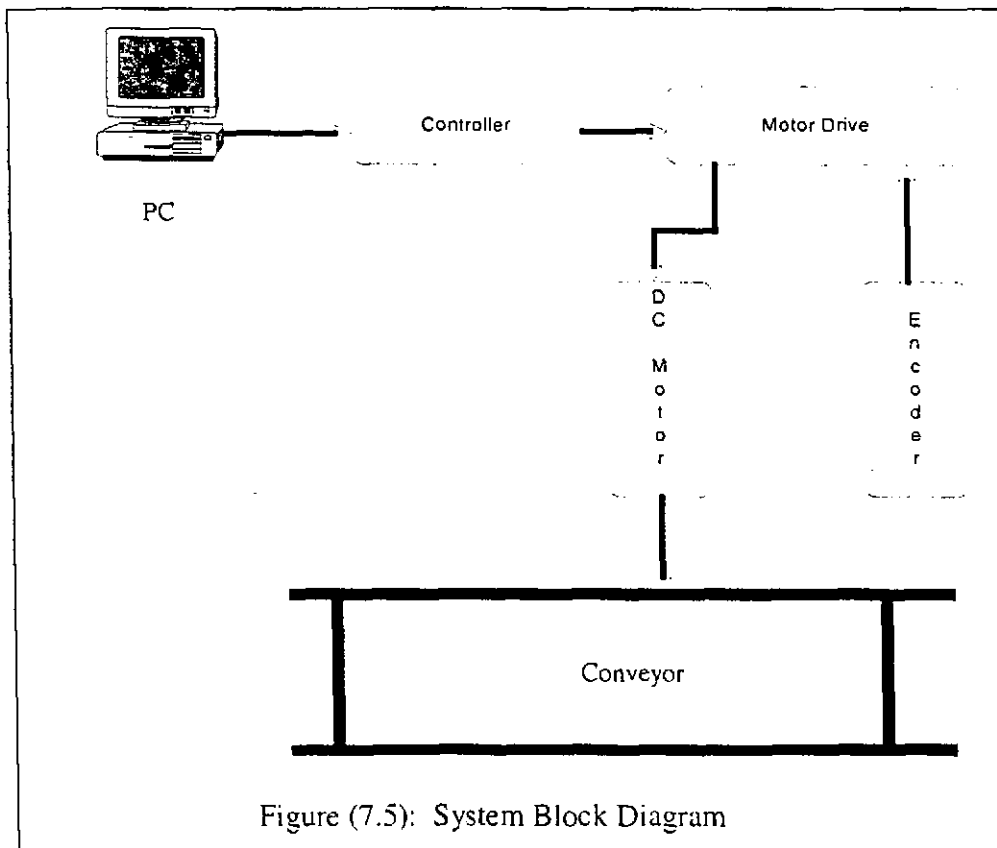
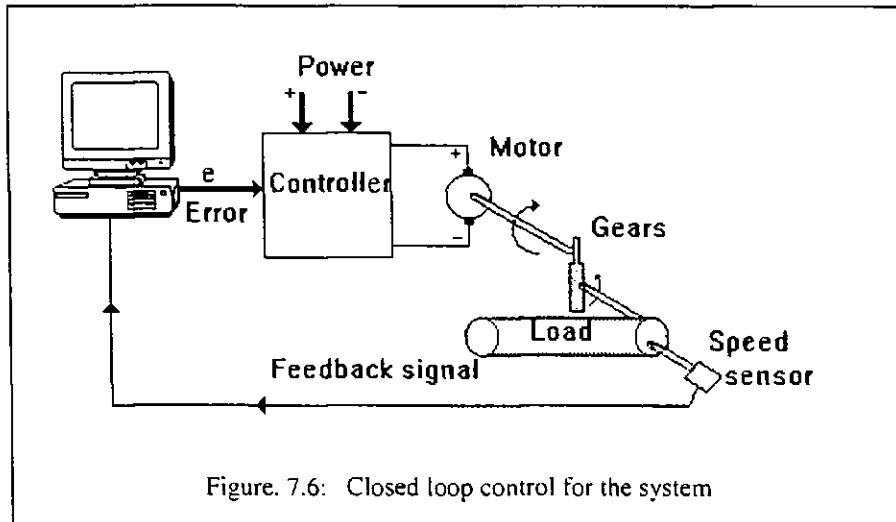


Figure (7.5): System Block Diagram

## 7.4 CONTROL STRATEGY

This section describes the operation of the belt position control system, the purpose of which is to cause the limbs of the user to move in a predetermined manner. The input element supplies information regarding the desired values of the variables of the controlled movement. This information is then acted on by the controller to steer the output to the desired values of movement. For a closed-loop system, a monitoring

element, encoder, to measure the output, was needed as well as a comparing element, to measure the difference between the actual output and the desired value of the input. The full closed loop control of the system is shown in Figure 7.6.



The encoder used to monitor the motor position is a Gray code high precision optical shaft encoder. The encoder is based on a disc attached to the motor's shaft so that, as the disc rotates, a light shining through the slots produces detector signals that are  $90^\circ$  out of phase with each other. The encoder records the position of the motor in a positive and negative direction. The following program was used to test that the encoder was functioning correctly:

REM Program to test the ENCODER

Axis [0.1,2] :REM the controller has three axes one step motor and two DC motors

Reset [0.1,2] : REM all axes set to zero whether they are used or not

GN = 0: : REM set all gains to zero

KV = 0: : REM set velocity feedback gain to zero

KI = 0: : REM set integral feedback to zero

KF = 0: : REM set velocity feed forward to zero

Abort : REM Disable the amplifier

LOOP

Print POS[0]; POS[1]; POS[2]; BOL : REM print positions of axis 0.1 and 2

ENDL

The above program works by disabling the amplifier and by setting all gains to zero so that the motor shaft can be moved by hand. The program prints on the screen the encoder value (position) of axes 0, 1 and 2 (each of these axes will control one unit). Therefore by moving the motor backwards and forwards the position changes.

### 7.4.1 Speed Control

The main task here was to output a fixed number of motor rotations and to reduce the motor's speed smoothly as the required number of revolutions was approached. In the software the speed to position characteristic ramps down smoothly to minimise any overshoot occurrence, this being achieved by reducing the speed non-linearly as the final position was approached. The characteristic curve shown below describes the approach chosen to reduce the speed. In Figure 7.7, the curve shows that the speed was reduced non-linearly, and hence ensuring that there will not be any overshoot when the final position is approached.

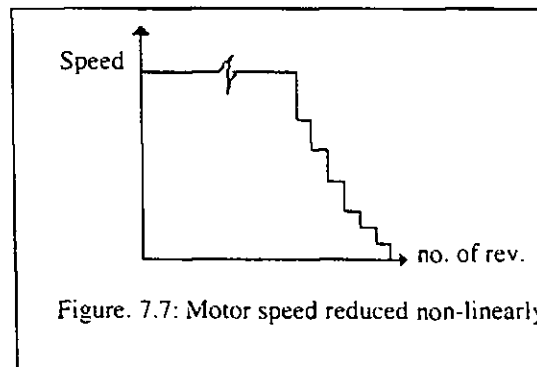


Figure. 7.7: Motor speed reduced non-linearly

In all positional moves the velocity profile was chosen to be an 'S' shaped ramp rather than the traditional trapezoidal ramp even though trapezoidal ramps provide the fastest point to point time for a given motor torque. The 'S' shaped ramp provides smoother motion but with the disadvantage of longer motion times. Therefore in order to get short, smooth moves, a modified 'S' ramp as shown in Figure 7.8 was implemented in the software program, where the acceleration increases rapidly, but tails off more slowly to provide a smooth approach to top speed or upon reaching the final position.

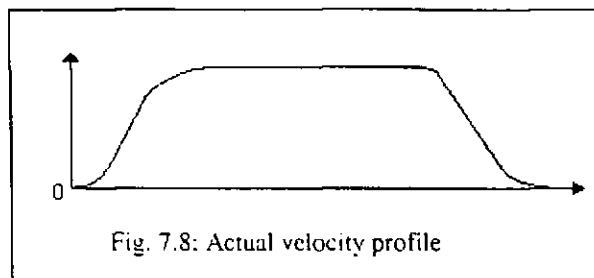
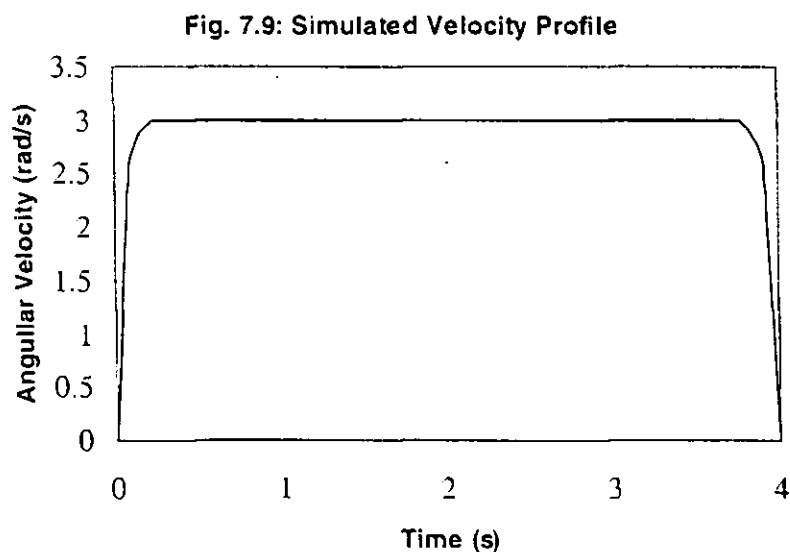


Figure 7.9 shows the simulated velocity profile that was obtained from the simulation programme using 3D Working Model. The cycle took 4 seconds to complete. The motor started initially from rest and the motor reached the target angular velocity in 0.1 seconds but it took 0.3 seconds for the motor to come to a stop. This was due to the implementation of a modified 'S' shape ramp which provided smoother motion but with a longer cycle time.



## 7.5 MOTOR CONTROL

The motor is controlled to minimise the error between demand (produced by the controller software) and the actual position measured with an incremental encoder. Every 2 milliseconds the controller compares desired and actual positions and calculates the correct demand for the motor. The torque is calculated by the use of

Proportional Integral Velocity Feedback and Velocity Feed forward, PIVF, algorithm. Control was achieved by applying a torque proportional to the error, there was a small error between demand and actual position. Tuning the drive involved changing the four servo loop gain,  $K_P$ ,  $K_I$ ,  $K_D$  and  $K_F$  to provide the best performance for this particular motor/encoder combination and load inertia. Because of the diversity of application, all these values (loop gains) are set to default to zero and the following procedure was used.

### 7.5.1 Procedure for Setting System Gains

The following is used as a rule of thumb for selecting the closed loop parameters of the controller:

1. For this system, The setting started by applying some feedback gain,  $K_D$ . It was started with a value of 1 and increased it until some sort of resistance was felt.
2. Once the feedback gain was set, some proportional gain,  $K_P$  was applied. It started off with a value which was a quarter of the feedback gain,  $K_D$ , i.e.  $K_P = K_D/4$ . As the motor started to vibrate, it was either to increase the feedback gain,  $K_D$ . or decrease the proportional gain,  $K_P$ .  $K_P$  was adjusted until the system step response was either critically (or slightly under) damped. Note, however, it was not necessary to apply fractional gains, i.e.  $K_D = 0.5$ .
3. For the value of  $K_P$  just found, the integral gain,  $K_I$ , was increased until the steady state error has reached an acceptable value (nearly zero). The integral gain,  $K_I$ , works by accumulating following error over time to produce a demand sufficient to move the motor into zero following error position, the integral gain,  $K_I$ , is usually a factor of 10 less then the proportional gain,  $K_P$ .
4. Finally, the velocity feed forward gain,  $K_F$ , was set to the same value as the velocity feedback gain,  $K_D$ . This had the effect of reducing the position lag during motion.



### 7.5.1.1 Calculations of Velocity Feed Forward Gain, $K_F$

The use of the calculated value of Velocity feedback forward under normal circumstances would give zero following error. The equation of the loop closure algorithm is as follows:

$$\text{Demand} = K_P \cdot e - K_D \cdot v + K_F \cdot V + K_I \cdot \sum e$$

Where:  $e$  is the following error (quad Count)

$v$  is the actual axis velocity (quad counts/sample time)

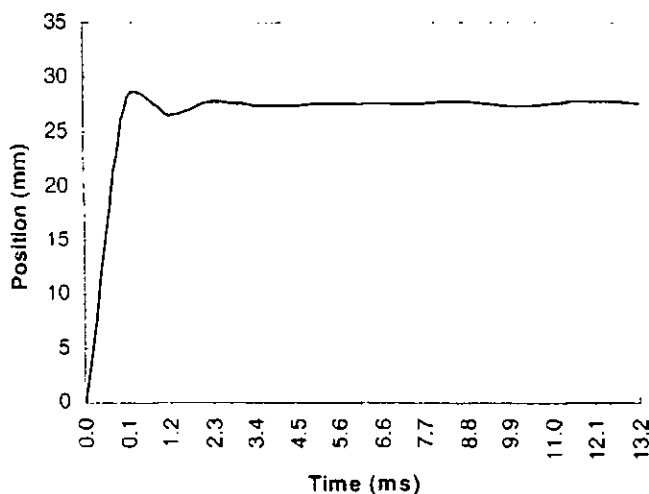
$V$  is the demand axis velocity (quad counts/sample time)

At 3000 rev/min and analogue voltage of 10V. This relates to 50 revolutions per second. Then calculating the number of quadrature counts per loop closure time yields a 1 ms loop closure time and since the DAC output has a resolution of 12 bits over the range of a -10 V and + 10 V, therefore + 10 V = 2048 counts. Therefore the feed forward term is given as 10.283. This calculated value would give zero following error in normal running. A following error ahead of the desired position occurs if  $K_F$  were increased above this calculated value and a following error behind the desired position occurs if  $K_F$  were decreased below this calculated value.

### 7.5.2 Proportional Control

The proportional controller multiplied the error by some constant, and when the gain was too high an overshoot occurred and the motor was vibrating back and fourth around the desired position. Proportional control was not suitable because the system became completely unstable. It was observed, however, that as  $K_P$  increased, the overshoot increased and although increasing  $K_P$  reduces the error and gave good transient response, but the overshoot still occurred as it is clearly demonstrated in Figure 7.10. For this type of control the steady state error did not and will never reach zero because the control action is the result of measuring the size of the error.

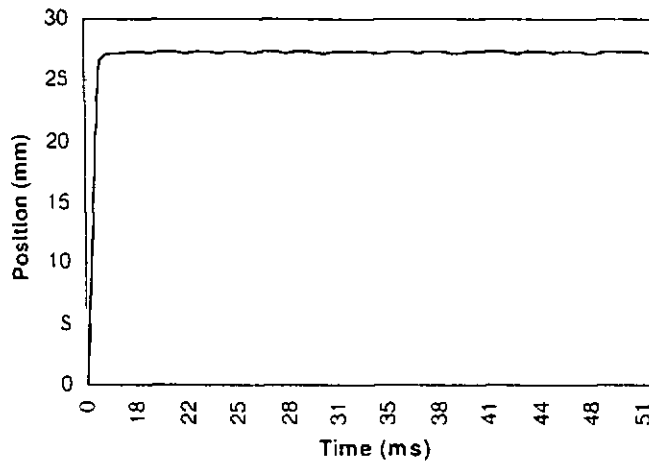
Fig. 7.10: Step response of the system for proportional (P) control



### 7.5.3 Proportional Derivative Control

To reduce the instability of the system a damping term was incorporated in the servo loop algorithm, called Velocity feedback gain,  $K_D$ . This Velocity feedback acts to resist rapid movement of the motor and hence allow the proportional gain to be set higher before vibration sets in. Since there was no positional error when the motor is stationary at a set point, Integral gain was not used (set to 0). It was then necessary to increase/decrease the proportional gain,  $K_P$ , or damping,  $K_D$ , to achieve satisfactory following errors, i.e. zero following error. It was observed that it was possible to obtain a response with practically no overshoot (i.e. critical damping) as shown in Figure 7.11, but still suffers from steady state error. To eliminate the steady state error a term called velocity feed forward gain,  $K_F$  was implemented. The calculations of this term is shown in section 7.5.1.1.

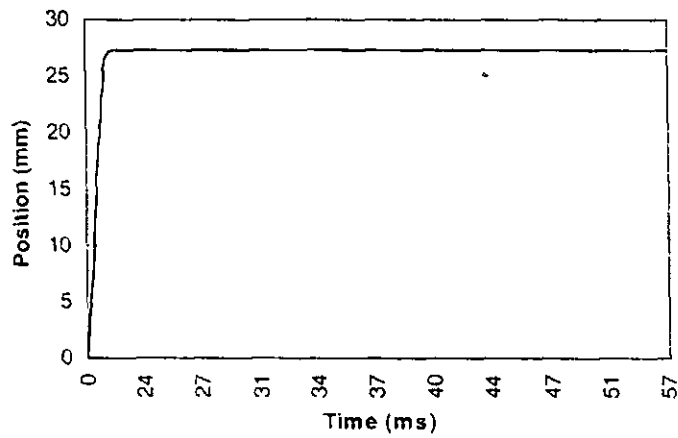
Fig. 7.11: Step response of the system for proportional plus derivative (PD) control



#### 7.5.4 Proportional Derivative Control Enhanced with Velocity Feed Forward

A final term that was included in the control loop was the velocity feed forward which was useful for increasing the response and reducing the following error without causing the motor to oscillate, provided that both the velocity feed forward gain,  $K_F$ , and that the other terms,  $K_P$ ,  $K_I$  and  $K_D$  in the closed loop were set up correctly. The velocity feed forward term,  $K_F$ , is a block which takes the instantaneous speed demand from the profile generator and adds it to the output block. The difference between velocity feed forward term,  $K_F$ , and the other terms is that  $K_F$  is outside the closed loop and therefore does not have an effect on the stability of the system. Once  $K_F$  was set up correctly, the system gave good fast response to changes in demand speed with lower following errors as shown in Figure 7.12. And left the closed loop terms only compensating for small errors in the position of the motor due to analogue drift. therefore correct setting of the velocity feed forward gain was,  $K_F$ , very important to get maximum response from the system.

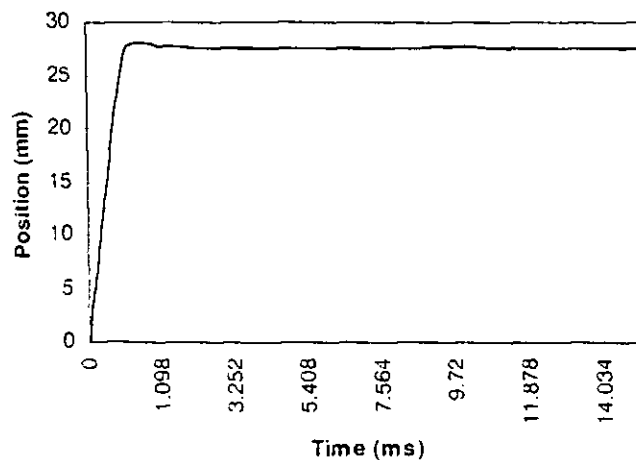
Fig. 7.12: Step response of the system for proportional derivative (PD) enhanced with velocity feed forward gain



### 7.5.5 Proportional Integral Control

Figure 7.13 demonstrates the effect of adding an integral term in the controller. Here the proportional plus integral (PI) control eliminates the steady-state with slightly increased overshoot. It was noted that PI has produced undesirable side effects of reducing speed and degrading stability.

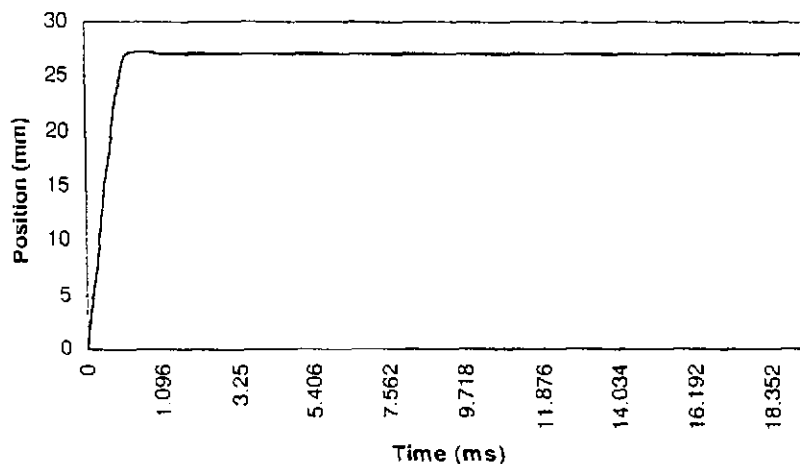
Fig. 7.13: Step response of the system for proportional plus integral (PI) control



### 7.5.6 Proportional, Integral and Derivative Control

In this system where positioning accuracy was required, it was necessary to position to within one encoder count. Proportional gain,  $K_P$ , was not able to achieve this because a very small following error produced only a small demand for the amplifier which was not enough to overcome mechanical friction and an integral gain,  $K_I$ , was used to accumulate following error over time to produce a demand sufficient to move the motor into the zero following error position. Integral gain,  $K_I$ , was set to very small values to avoid instability during moves. As shown below the step response of the motor in Figure 7.14, there was a slight overshoot which settled quickly within 1.1 milliseconds. Different combinations were tried to obtain the best response from the motor. The step response was the best response obtainable for different values of  $K_D$ . It was not possible to achieve the desired final position with no overshoot.

Fig. 7.14: Step response of the system for proportional plus integral plus derivative (PID) control

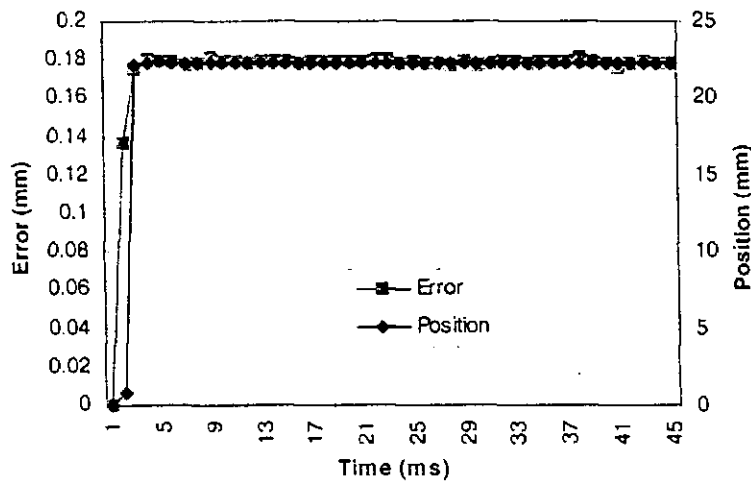


## 7.6 THE PATTERNER MACHINE PERFORMANCE

The Patterner Machine performance was judged against accurate positioning. Due to the sensitivity of the project, accurate and precise positioning was essential. As the plots below demonstrate, the positional accuracy of the motor only was within  $\pm 0.175$  mm. The data in Figure 7.15 was captured through the subroutine listed below,

capturing this type of data was essential in analysing the motor performance. The subroutine captures the data and then uploads it to an application program such as Microsoft Excel where the data can be plotted and analysed. Table 7.1 lists the accuracy of the movement of the steps of the machine to and from the desired positions.

Fig. 7.15: Positional Error of the Patterner Machine



*Capture Subroutine:*

```

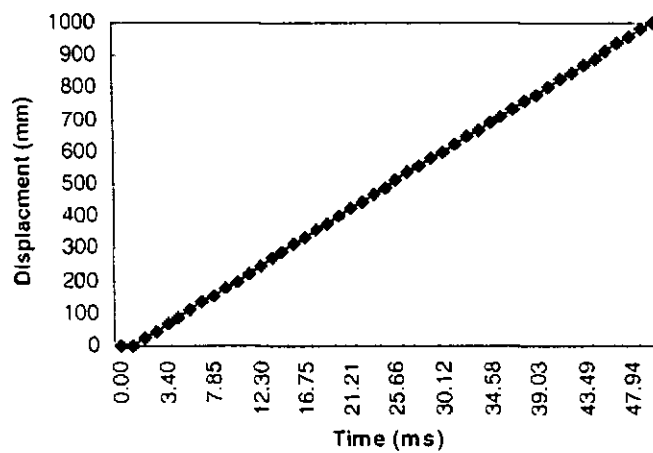
Dim offline data (4000)           : Rem Reserve data points
Datatime = 4000                   : Rem Capture 40 seconds of data
Capture.1 = 3                     : Rem Capture axis 1 position on memory card
MR = 200                          : Rem Perform a move
MR = -200
Pause Idle                        : Rem Wait for axis to become idle
For data = 1 To 750               : Rem Upload the data as a CSV file
    ? data (data)                 : Rem importing into Excel
Next
    
```

Table: 7.1. Position accuracy and repeatability of The Patterner Machine

Terminology	P1	P2	P3	P4	P5	P6
Accuracy mm	0.1754	0.3549	0.3969	0.4896	0.5278	0.5734
Repeatability mm	± 0.566	± 0.734	± 0.780	± 0.40	± 0.671	± 0.442

Figure 7.16 shows one segment of the actual displacement of the Patterner Machine. As the Patterner Machine started from rest and travelled along at a constant speed, the actual displacement lagged slightly due to time needed to respond to the input signal. This result was compared to the simulation result created by the constructed computer model.

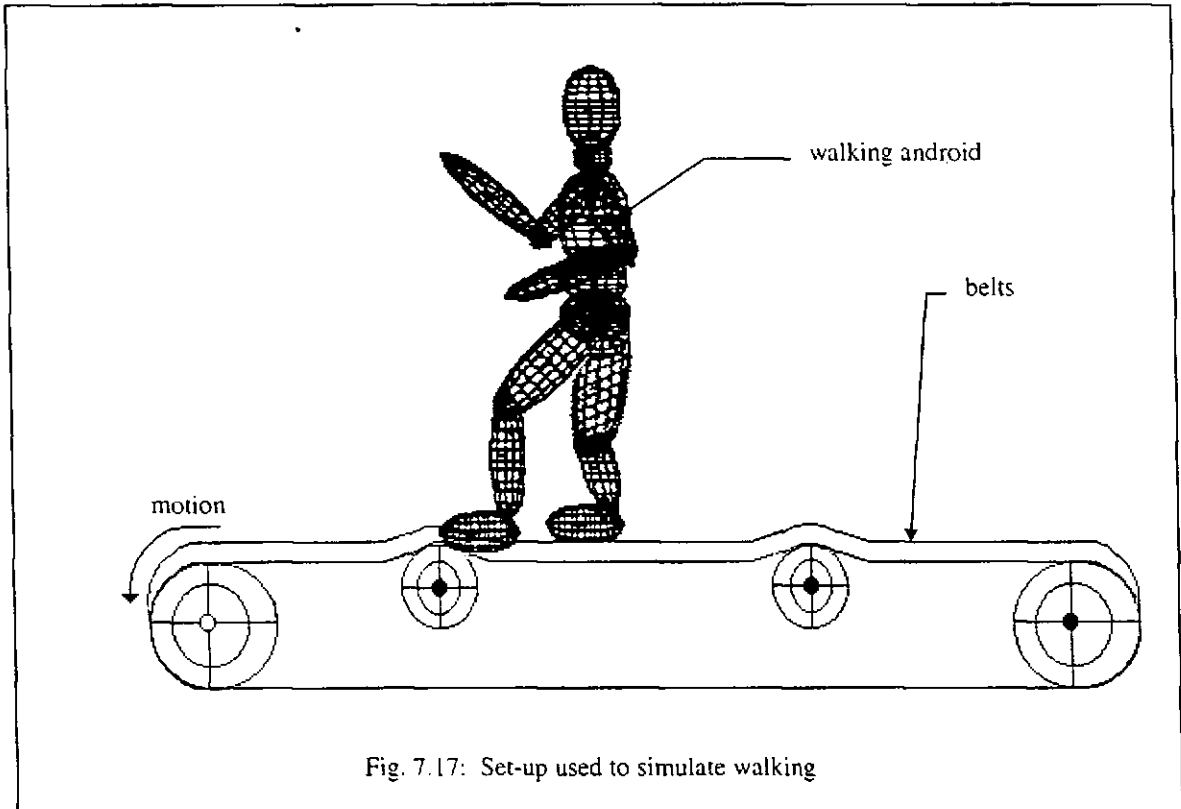
Fig.7.16. Actual Displacement of the Patterner Machine



### 7.6.1 Combining Motion and Surface Contact

Because of the nature of the project surface contact is an essential part in carrying out the rehabilitation treatment of the brain injured patients. Touching is an important factor in training the cerebellum (the region of the brain mainly responsible for co-ordinating movement). Therefore, an android was built to simulate the actual patient's walking. The Model was built using the simulation package called ADAMS. The model was created to have the joints that supply motion and surface contact between its feet and the two units (two axes) designed for walking. The model contained two contacts and a connector. A harness was designed to maintain the android in an upright position but the feet were not strapped. Note however, the harness allowed the model to translate forward and up and down. The results obtained are shown in Figures 7.18 to 7.20. Figure 7.17 shows two axes of the set up used to simulate walking. Two pulleys of equal diameters were constructed as a master slave system and two smaller pulleys were placed in the middle under the

moving belt to simulate walking and to show the bending of knees and the movement of the hips.



Figures 7.18, 7.19 and 7.20 show the movements of Right and left legs displacements in degrees and the displacement of the right and left elbows. The android started the walking motion as in Figure 7.17 from rest as the motor started to move. As the right leg ankle (Rknee) and the right leg knee (Rknee) advanced forward, the hip (Rhip) was lifted up to a displacement of  $30^\circ$  within 0.2 seconds. The ankle movement was somewhat limited to within  $0$  to  $10^\circ$  in 0.2 seconds, where as knee took 0.4 seconds to move more than  $60^\circ$ . It was noted, however that as the foot on the peak point of the pulley, the knee and the ankle were on the same level at  $0^\circ$ . As the foot started sliding down the other half of the pulley, the displacement of the hip gradually started decreasing associated with a decrease of the displacement of the knee and the ankle. At the time of 1 second, the right leg took it is normal position and the left leg started to complete the walking process, Figure 7.19. Note, however, the actual movement of the left leg started effectively completing the walking process at 0.8 seconds. Here the



left leg ankle (Lankle) at  $-20^\circ$  and left leg knee (Lknee) at  $-40^\circ$ , where as the left foot hip leg started at  $-10^\circ$  and this was due to the posture of the way humans walk.

Fig. 7.18: Right Leg Walking Displacement

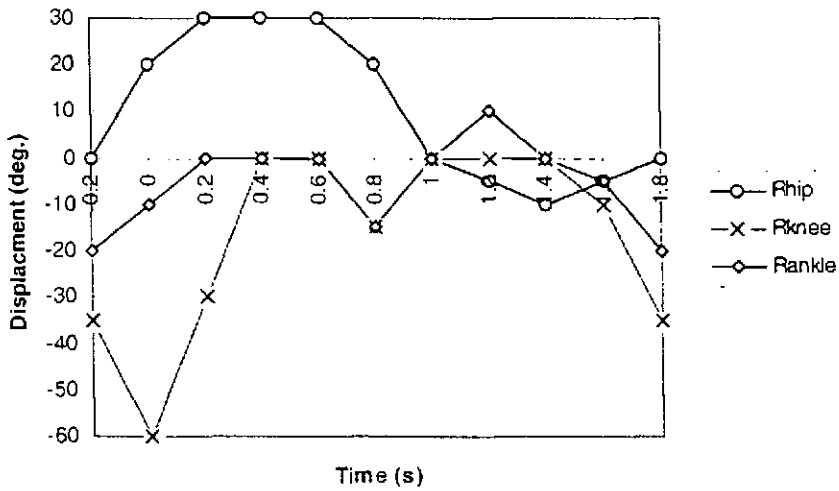
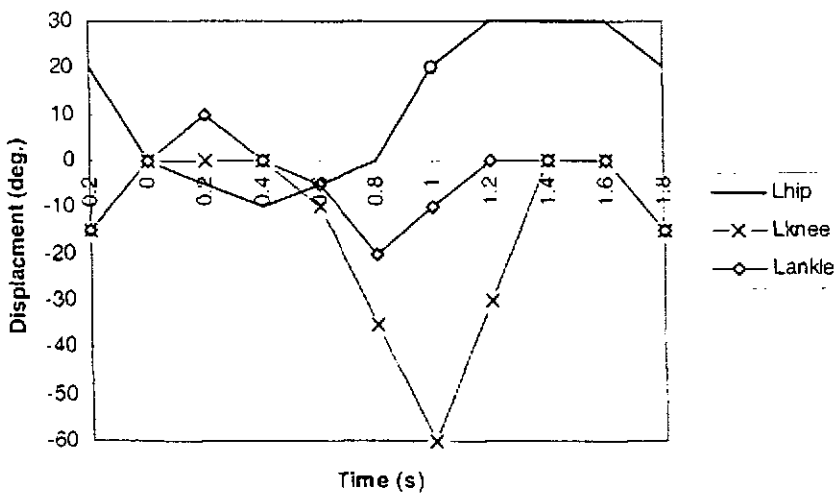


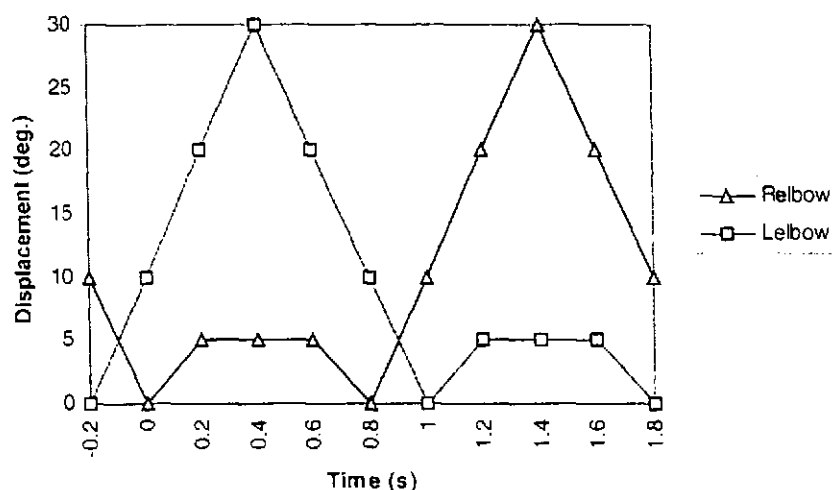
Fig. 7.19: Left Leg Walking Displacement



Figures 7.18 and 7.19 may have had given a better clarification of the movement if they were superimposed, but they would have been very difficult to analyse. Figure 7.19 shows the movements of the right elbow (Relbow) and left elbow (Lelbow) when performing walking. By comparing the left hand elbow motion with the right leg

motion in Figure 7.18, it can be observed that as the right leg was lifted up the left elbow moved the same displacement as the right leg hip while the movement of right elbow was somewhat limited to  $5^\circ$ . And as the right leg descended so did the left elbow, which was associated with a right elbow movement as the left leg was ascending.

Fig. 7.20: Right and Left Elbows Displacements



## 7.7 SOFTWARE LANGUAGE AND ALGORITHM

The language used to control the motor is a BASIC-like motion control language, called MINT. The name MINT, stands for Motion INTerpreter. This language is structured from BASIC, custom designed for the Euro System controller. MINT provides a wide range of powerful commands for complex applications. It also includes various routines, mainly written in C, to assist the implementation of host computer communications. MINT programs consist of two files. The configuration file that stores information relating to the machine set-up, such as the servo loop gains. The program file stores the actual motion control program. The following is a description of the main modules in the program, reference should be made to the flow chart for each section and the overall program is given in Appendix E, the structure of the program is given in Figure 7.21.

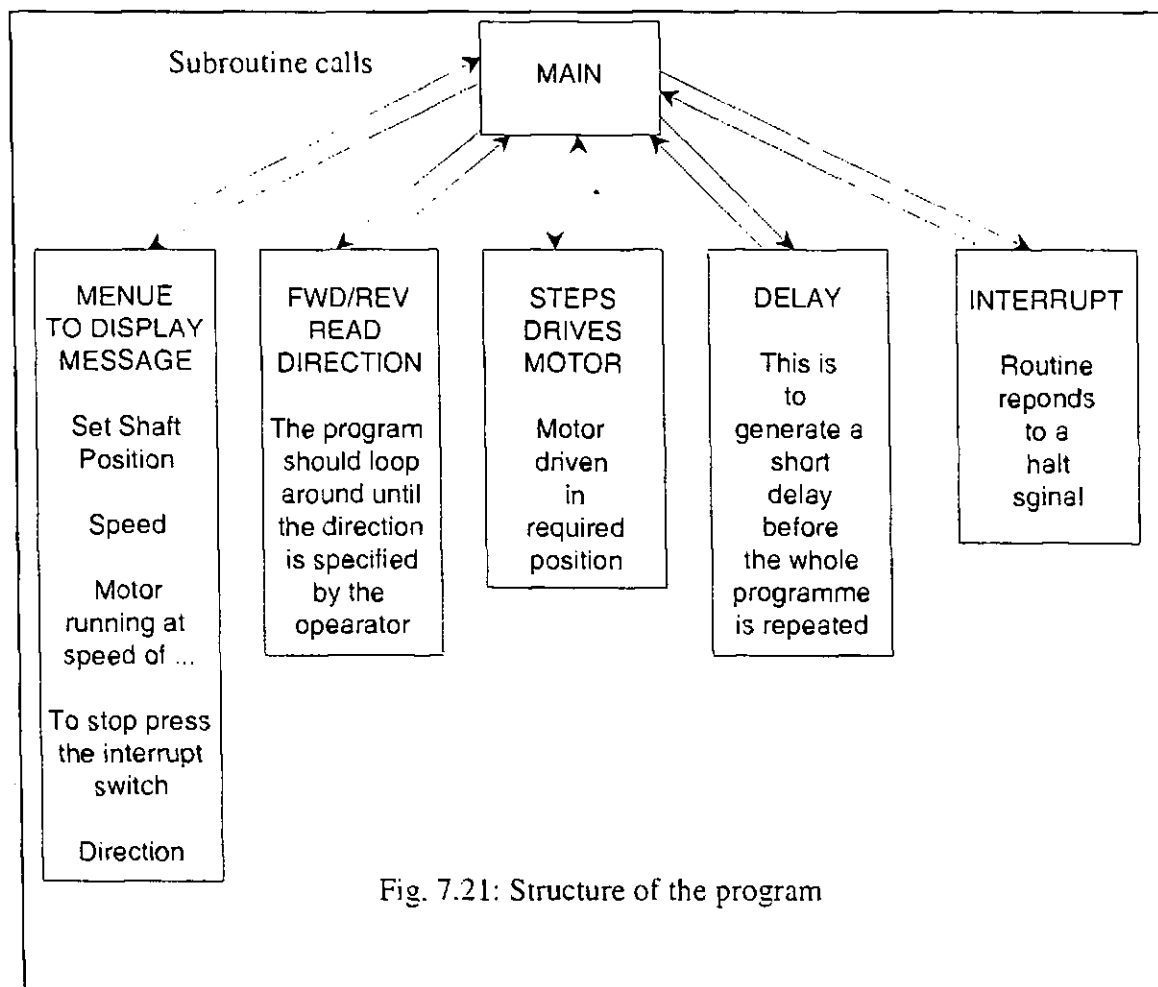


Fig. 7.21: Structure of the program

### 7.7.1 Description of the Program Subroutines.

1. **MAIN**. This subroutine in Figure 7.22 sets a pointer in high language to the memory address of the first display message and calls **MENU** to display a message that sets shaft position, speed and direction. Subroutines forward (**FWD**) and reverse (**REV**) is called to read the key board only if the units need to be adjusted to fit the size of the patient. This program loops around this call until the operator presses (**F**) for forward or (**R**) for reverse. Once the desired position is reached the program loops until an end command is issued then the program jumps back to menu where a particular patterning technique must be selected. Subroutine **STEPS** is called for the chosen technique and tells the operator to enter the number of units to be used and their identification numbers and then to set up the speed and the length of the steps in accordance with the instructions giving by the brain

injury institute. Finally, subroutine DELAY is called to generate a short delay, before the whole program is repeated.

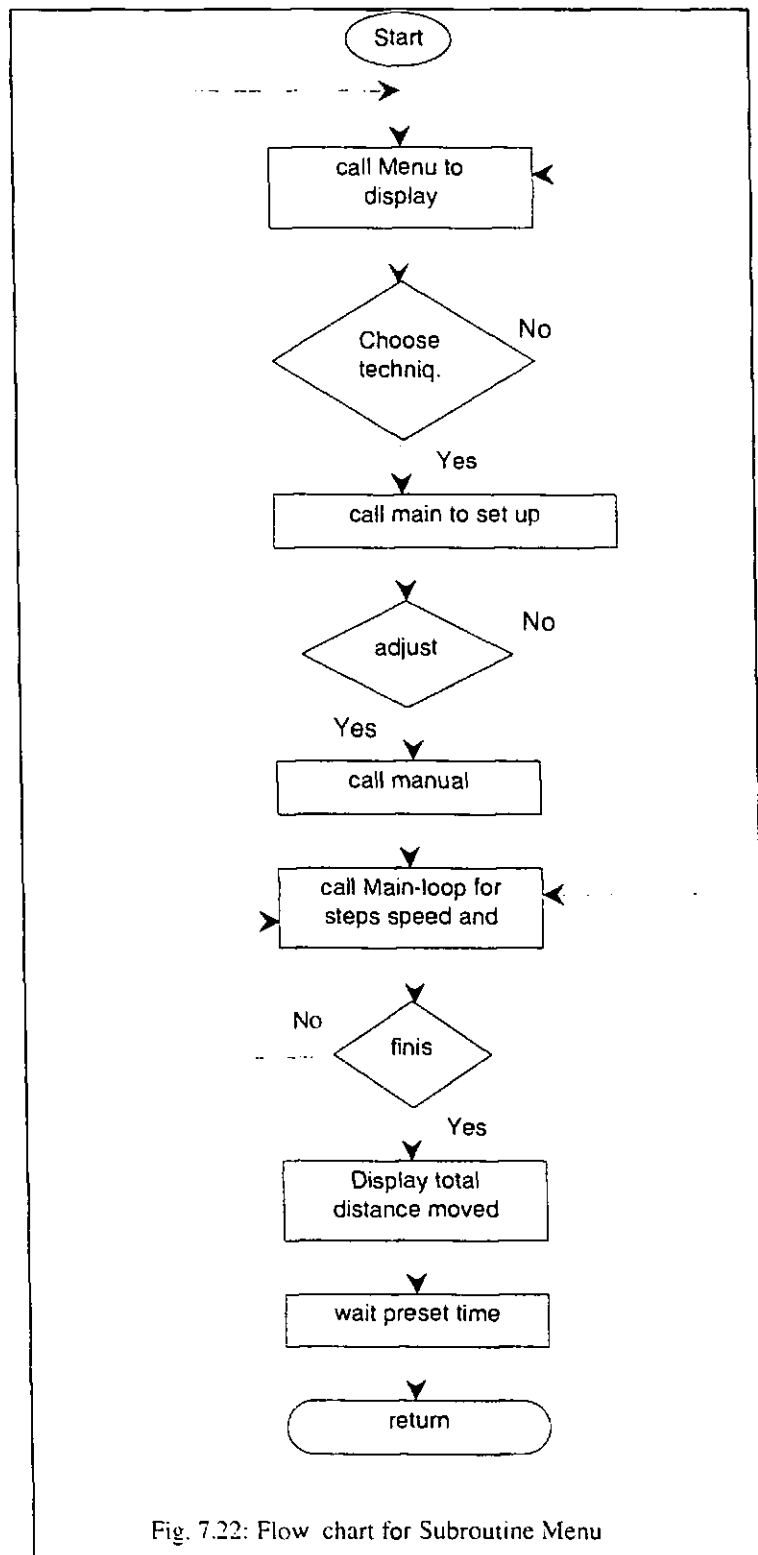


Fig. 7.22: Flow chart for Subroutine Menu

2. *MENU*, this is a subroutine that describes the method of patterning and the safety procedures along with point form instructions on how to set up the units, Figure 7.35. This program is designed to loop until a desired key is pressed.
3. *FWD/REV*, is a subroutine that enables the operator to set the units in a suitable manner to fit the size of the patient. This subroutine must only be used when the patient is off the units, Figure 7.23.

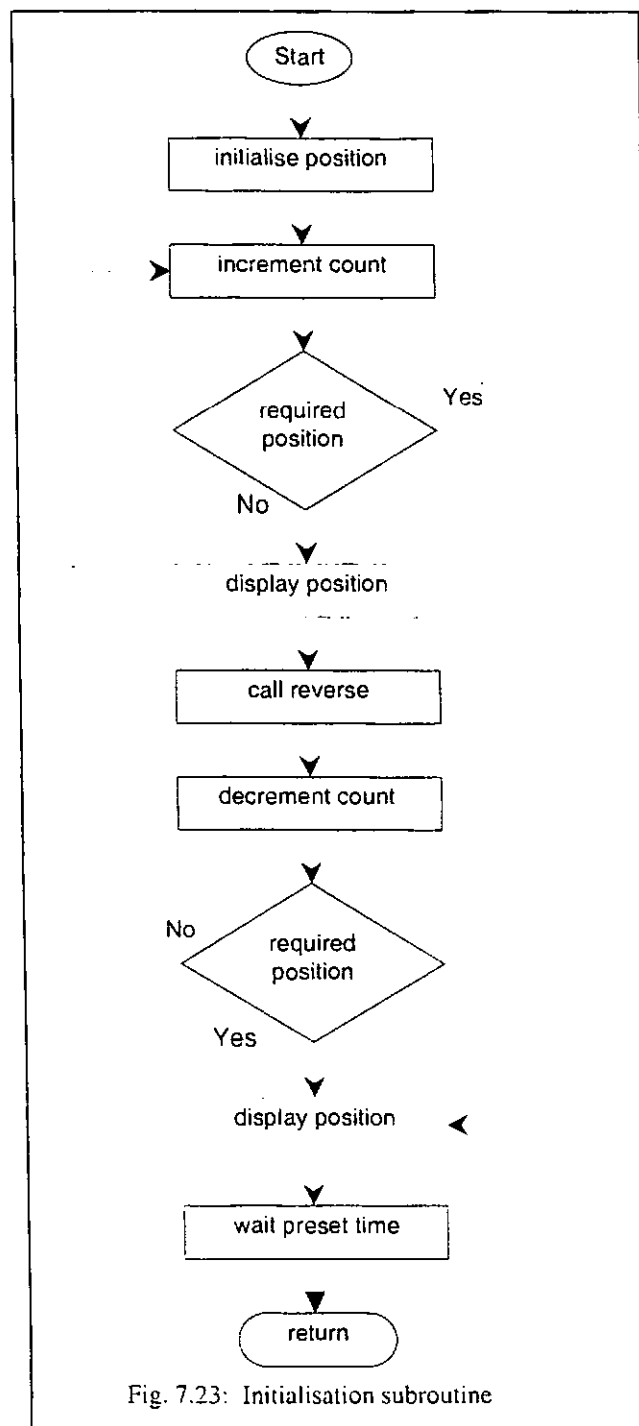


Fig. 7.23: Initialisation subroutine

4. STEPS is a subroutine, shown in Figure 7.24, which loops and scans the keyboard until the length of step and the speed at which the motor will run the required number of steps are entered. In other words this subroutine allows the operator to enter the desired distance in mm and it displays the number of steps and on the second pass the speed in mm/s at which the motors will run must be entered within the specified limits.

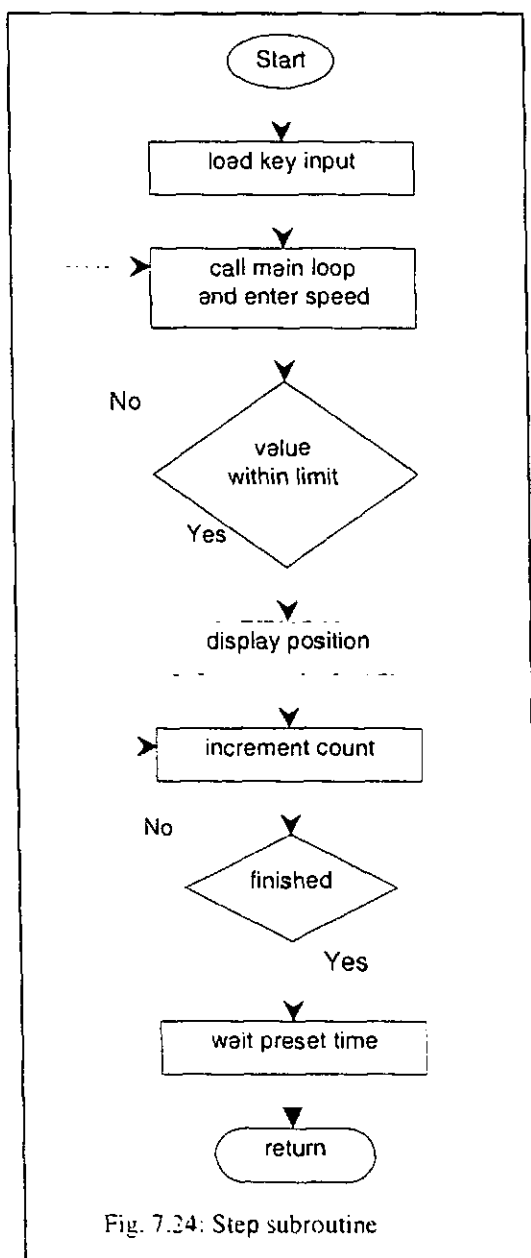


Fig. 7.24: Step subroutine

5. INTERRUPT is a subroutine that responds to a halt single for any reason (CTL E).

## 7.8 SAFETY STRATEGY

The main condition to be met is fail-safe criterion, defined by the European Standard as “a theoretical situation which would be reached if a safety function remained unchanged in the case of a failure of the power supply or any component contributing to the achievement of this situation” [European, 91]. Therefore it is essential that full safety measures are taken with electrical and moving machinery. Before personal are allowed access to moving parts, the drive and motor must be isolated from the electrical power source by means of switches which are capable of braking the maximum current. Limit switches are used to protect the units by connecting them to the controller. For emergency stopping of the motor, the use of the velocity command signal, VCS, clamping will stop the motor at the peak current set. To ensure the motor stops in the event of a system malfunction, the motor must be dynamically braked by a fail-safe contactor. The system equipment embodies primary protection such as limits, stops and guards, it also embodies secondary protections provided by the sensors and the software program. The recommended safety sequence for emergency braking is as follows.

- Clamp VCS to zero to stop the motor using the peak current of the drive, a 2 ms reed relay must be used.
- After VCS clamping stops the motor (20 to 100 ms), disconnect the motor from the drive and connect dynamic braking resistor across the windings. A contactor operating time of 20-30 ms may provide enough delay before applying the dynamic braking, which will stop the motor if the drive has failed.

### 7.8.1 Dynamic Braking Resistors

The value of the braking resistor of  $0.33 \Omega$  assuming maximum bus voltage is used, and peak motor torque can be applied. Braking will be at somewhat constant torque down to one third of maximum speed, followed by exponential speed decay. Here the motor is made to act as a generator. The armature is disconnected from the supply, but it continues to rotate and generate a voltage. The polarity of the generated voltage

remains unchanged if the direction of field excitation is unaltered. But if the resistance is connected across the coasting motor, the direction of the armature current is reversed, because the armature represents a source of power rather than a load. Thus a braking torque is developed, exactly as in a generator, tending to oppose the motion. The braking torque can be controlled by the field excitation and armature current.

### 7.8.2 Dynamic Braking and Safety Contactor

For safety reasons a dynamic braking system was implemented, Figure 7.25. To stop the motor in an emergency and bring it to a standstill as quickly as possible, VCS is set to zero by clamping VCS + to VCS-. Motion stops in 100 ms, at maximum load (worst case) and in 20 ms at minimum load (best case).

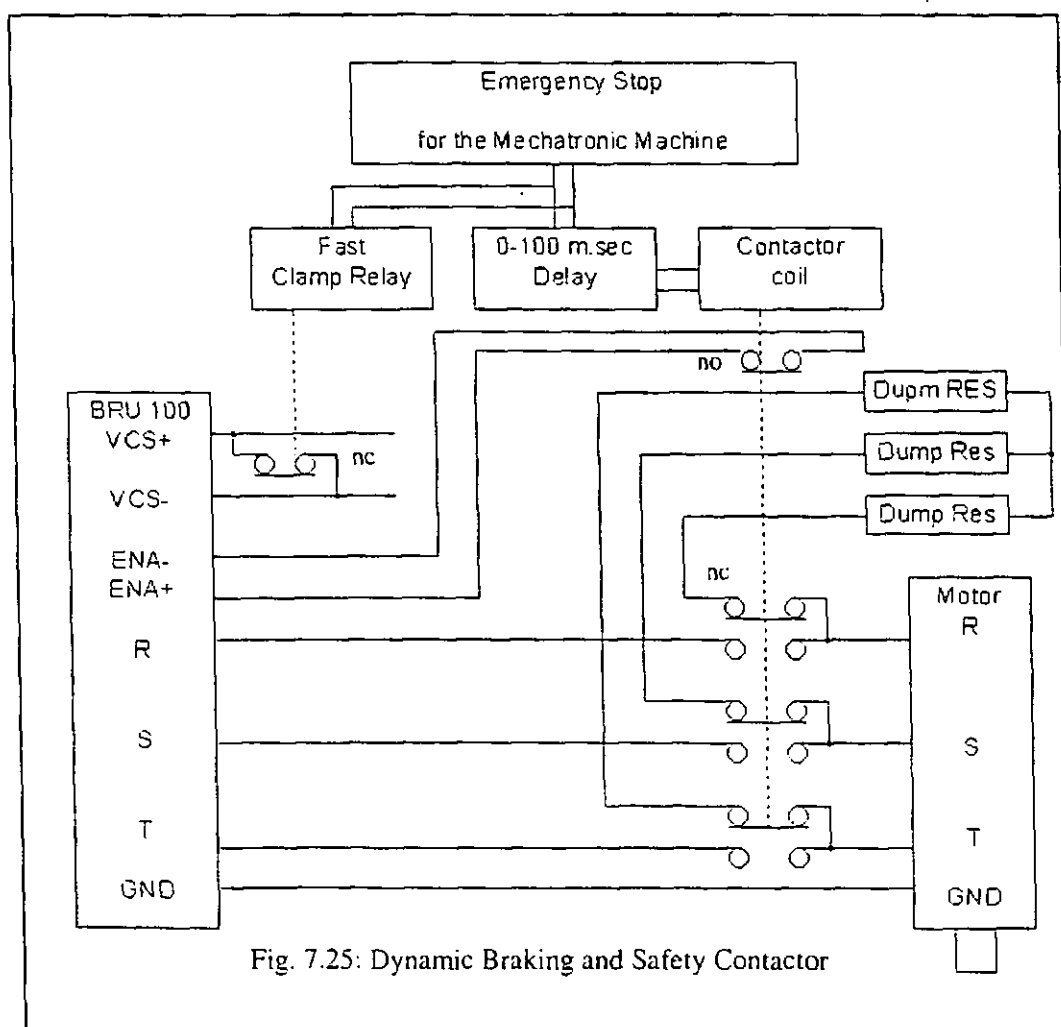


Fig. 7.25: Dynamic Braking and Safety Contactor



Generally the motion will stop in 20-100 ms depending upon the load inertia, maximum possible speed and current limit setting. Connecting the braking/dump resistors and disconnect the drive by changing over the main contactor to coincide with the motion halting and allowing for the contactor delay time, typically of 20-30 ms. Dynamic braking provides back-up stopping in the event of a drive failure, or loss of supply. Dynamic braking provides little torque at low speeds when the generated voltage is low. The contactor will fail-safe to the disconnect/dynamic braking position on loss of power. For a more safer system, the motor and the drive are completely isolated from the power source by a switch capable of braking maximum current. The block diagram in Figure 7.25 is a safety arrangement to protect both the user and the operator.

## 7.9 Experimental Results

The single axis prototype was assembled and tested for control strategy fulfilment, accuracy and repeatability. The full unit consisted of the frame (which includes the belt, motor, encoder, gear box and pulleys) and the control system (which includes the controller board, transformer, motor drive and the computer). The machine was also tested for adjustment accuracy, to cater for patients of different sizes, i.e. adjustment of straps on the belts depending on the size of the patient.

### 7.9.1 Safety Test

The Patterner Machine safety procedure was tested by running the software program as if the machine was required to perform an intended movement while the disable switch was active. Although the program asked the operator to enter all the relevant data the machine did not move, indicating that the safety strategy was working satisfactorily.

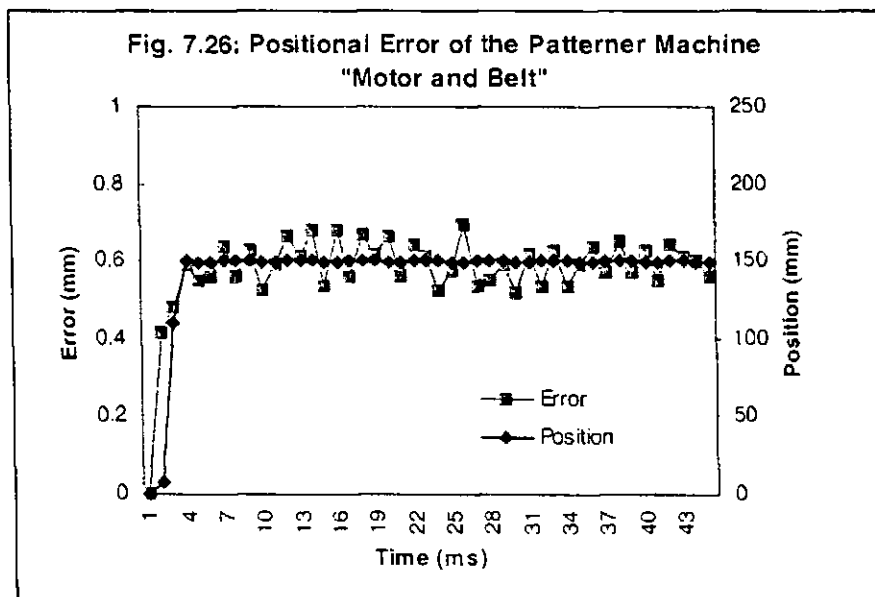
### 7.9.1 Performance Test

The performance of the Patterner Machine was tested by checking its conformance with stepping distance, positional adjustment, repeatability and accuracy. The accuracy of the system (belt, motor and high precision encoder) as shown in Table 7.2, was within  $\pm 0.632$  mm and the repeatability accuracy was within  $\pm 0.692$  mm over six positions.

Table: 7.2. Position accuracy & repeatability of The Patterner Machine (Motor & belt)

Terminology / Position	P1	P2	P3	P4	P5	P6
Accuracy mm	0.50	0.62	0.592	0.63	0.67	0.78
Repeatability mm	$\pm 0.566$	$\pm 0.739$	$\pm 0.680$	$\pm 0.70$	$\pm 0.621$	$\pm 0.675$

Figure 7.26 demonstrates the positional accuracy of the Patterner machine. The data was captured using the capture subroutine presented in section 7.6. The accuracy of the systems was within  $\pm 0.692$  mm. The allowable following error in the software program was set to  $\pm 1$  mm.



## 7.10 SUMMARY

The novel design aspects and construction were investigated. The simulation results obtained were confirmed using the actual testing of the Patterner Machine. The displacement of the actual model of the Patterner Machine lagged slightly the simulated model due to the damping effect, which is the time needed to respond to the input signal. The desired positional accuracy was achieved within  $\pm 0.175$  mm. A safety control system was developed that ensures safety for both the user and the operator. A novel control strategy was developed where best control method was implemented. Proportional derivative (PD) enhanced with velocity feed forward gain control enabled the system to be stable and the required accuracy in terms of position was achieved. To drive the motor, a modified "S" shaped velocity profile was preferred to the traditional trapezoidal ramp because the former provides smoother motion than the latter. A Gray code high precision optical shaft encoder was used as a feedback parameter to measure the displacement position of the Patterner Machine. A sophisticated software was constructed to ensure safety and ease of use. The program software allows the operator to set the recommended speed along with the recommended step distance set out by BIBIC. A fail-safe system was developed and implemented by the use of dynamic braking and safety contactor.

# Chapter 8

## CONCLUSIONS AND FURTHER WORK

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*'The work goes on, the cause endures, the hope still lives and the dreams shall never die.'*  
*Senator Edward Kennedy, c. 1983.*

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### 8.1 CONCLUSIONS

The aim of this research was to investigate novel design and construction aspects of a mechatronic device which can perform the tasks that a brain injured patient can not naturally develop for one reason or another alone without patterning. To study and develop mathematical expressions for the human movements of the limbs involved in the patterning techniques and other related joints. To analyse the forces the human body exerts on the machine such as push and pull forces and instant and sustained forces. Also to investigate the linear kinematic such as displacement which is a measure of how far a body is moved from a starting point in a given direction, distance which is simply a measure of how far an object has travelled in getting from one point to another and speed which is a measure of the distance covered by an object in a given time. To also develop an optimal control strategy using the available conventional methods of control as well as the implementation and development of safety enhancement mechanism. Finally one of the main concerns was to develop the Patterner Machine to perform the techniques of patterning without compromising the system integrity with a cost the majority of brain injured patients can offered.

### 8.1.1 Surveys and Measurements

The first step that was taken towards achieving this goal, was a detailed research into the areas of human factors, ergonomics, anthropometric and statistics related to brain injured patients and other related physical illness. Also investigating and analysing patterning systems available to date that particularly deal with brain injury. Emphases were put on studying the suitability of the these available patterning machines and their use, i.e. whether they are used for patterning or just to help brain injured patients cope with their disability. Since information regarding this area of research was scarce, surveys for age groups of 6 months to 13.5 years old regarding movements in prone positions, which mimics the real creep and crawl a healthy child experiences were conducted. These surveys and the results obtained using high video equipment were used as the main back-bone of designing the frame along with other data collected from the British Institute for Brain Injured Children and reference books specialised in the field of measurements of human body dimensions related to patterning such as data collected by H. Dreyfuss and associates and W. Woodson.

Statistics showed that approximately two million of the worlds new borne babies per annum are born brain injured and that it would cost a government about £20,000 to care for brain injured person and an estimated cost of £2.7 million pounds as the life treatment cost for a person with a brain injury.

Human factors research regarding the performance of the human head, arms and legs configuration over a wide range of movements and the development of a mathematical expression which covers the movements of the human body in the desired prone position was undertaken. Investigations into the available machines, revealed no information regarding the dimensions that ought to be used for the purposes of designing such a patterning device.

### 8.1.2 Available Patterning Machines

A review of rehabilitation robotics and mechatronic research highlighted the diversity of work within this small area of research. All efforts were concentrated on helping the brain injured cope with the disability rather than help them recover from it. Therefore, there is undoubtedly a need for such a system (a remedial device) to significantly improve the lives of such a group to benefit from their contributions to society and most importantly make them depend on themselves.

Previous work that involved in carrying the patterning techniques manually showed that the human brain can be stimulated through physical activities and that the central nervous system can pick up the information as long as there are some healthy brain cells. Investigations and analysis of the available patterning machines concluded that The discussed patterning machines did to some extent perform the required tasks of homolateral creeping and crawling and cross pattern creeping and crawling. However none of these were designed to perform walking although it is natural for a child to walk after having learned how to creep and crawl. Two of the four designs did not fulfil the requirements of patterning since the element of the floor was not considered. These designs provided no specific physical measurements pertaining to brain injured patients therefore it was necessary to undertake full scale surveys among healthy and brain injured children to set out the outlines for an optimum kinematic arrangement for the Patterner Machine.

The review has also highlighted some important stages which were considered before laying out the final kinematic arrangement of the mechanised device. Such considerations are: identifying the most important tasks as defined by the British Institute for Brain Injured Children, concentrating on an age group who are most likely susceptible to brain injury and consultation of patterning specialised therapists before the first stage of the kinematic arrangement was even put together.

### 8.1.3 Patterner Machine Design and Construction

The specification of the kinematic arrangement was the central point in the design process which provided a bridge between the compiled data on one side and the kinematic design on the other. All design requirements were centred on implementing the patterning technique with a kinematic design which allows the machine to perform the four patterning techniques (Homolateral creep and crawl and cross pattern creep and crawl) required, as well as the fact that the system has to be safe, reliable, robust, ease of use and more importantly to be operated at the home environment.

The dynamic measurements of the human body in the prone position and the advises of the directors of British Institute for Brain Injured Children were the central point in laying out the final design specifications of the kinematic arrangement of the Patterner Machine (mechatronic device). The dynamic measurements were particularly important in terms of the width and the length of the belts and also the height off the floor. Considering the fact that the Patterner Machine would be used at least for ten hours per day, a minimisation of the noise level was essential as well as making the Patterner as enjoyable as possible for both the user and the operator.

A review of direct-drive pneumatic, hydraulic and electrical rotary actuators showed that electrical rotary actuators are more suited for this type of application than the other two. Therefore an extreme care was taken in choosing the actuator, which was a vital component in the design of the prototype. The need for safe operation, and yet accurate positioning, has led to the use of a permanent magnet motor equipped with 1000 line count encoder and a gear box of a 30 : 1 ratio with zero backlash. And since high speed was not an objective the inertia mismatch was made as low as possible with the choice of a high but suitable gearbox ratio. A suitable material was chosen to build the frame of the prototype (single axis). Aluminium was a suitable choice because of its light weight compared to mild steel (Aluminium is about one third the weight of mild steel) and also because of its excellent corrosion resistance, which meant that it did not require any

painting unlike mild steel. Another advantage of aluminium that it could be easily machined and fabricated. Other materials such as mild steel and plastic were eliminated because of weight factor for the former and the lack of the rigidity and strength needed for the unit for the later.

#### **8.1.4 Force Interactions and Simulation Results**

A computer model of the kinematic arrangement was created using ADAMS/View. The model was built to scale, and the part builder was used to create the geometric elements needed for the belt, pulleys and the frame. All mass and inertia property calculations were considered. Creating an exact replica of the system was not possible because the software was not able to support such a system, however great efforts were put to create all the necessary constraints and the joints for the modelled prototype. The computer model was verified, analysed and animated with satisfactory results.

Motions of the human body in the prone position was monitored and measured by designing and developing a strain gauge force transducer capable of measuring instant and sustained forces. The experiment was divided into age groups according to the increase and decrease of force as the human subject grows up. The experimental results showed a variation of forces between the age groups. It showed that age group 26 to 40 years old exerted maximum instant and sustained forces where as children of age group 6 months to 2 years exerted the least amount of instant and sustained forces. Analysis of high speed video cameras of the natural movements of humans. Derivations of mathematical expressions of the desired patterning in the prone position have played a major role in setting up the final design specifications of this mechatronic system.

#### **8.1.5 The Patterner Machine Control Strategy**

To develop a safety critical control procedure for the mechatronic system (the Patterner Machine). Step response tests were carried out under a variety of algorithms in order to



achieve zero error and the best performance in terms of fastest settling time. Of the five control types implemented, proportional derivative, PD, control and an enhanced velocity feed forward gain proportional derivative control produced the best salve performance in terms of zero steady state error with faster settling time than the other three strategies. Therefore, it was possible to obtain a response with practically no overshoot (i.e., critical damping). Since patterning is a repetitive process, it was desired to achieve a reasonable repeatability positional accuracy. The achieved repeatability and accuracy, were seen to be very satisfactory, Table 7.2, with a repeatability of 0.7mm and an accuracy of 0.62 mm. The performance of the Patterner Machine was tested using ADAMS, where only walking was analysed since it was not possible to simulate the six units. The results indicted smooth and co-ordinated movements of the two units with a positional accuracy of  $\pm 0.63$  mm.

#### *8.1.5.1 The Hardware/software Design*

The hardware interfacing between the computer and the DC motor was constructed. The interface involved a use of a personal computer and a serial link to control the circuitry that drove the motor. A software program which simply sends control signals to the DC motor was constructed using Cmint which is a combination of C subroutines and visual basic. Further more, the project demonstrated a relatively sophisticated program, which allows the operator to enter details of the required DC permanent magnet motor movement which then implements these movements. The project was extended to allow the operator to specify the stepping length of each individual unit of the Partner Machine as well as adjusting the units to suit the size of the patient. Additionally the operator could specify the rotational speed of the units. Precise positioning and accurate continuous rotational speeds were achieved. Description of the modules within the program were made using flow chart for each section. The overall program listing is presented in the appendices.

Finally a comparison of the Patterner Machine and the other available patterning machines is presented in table 8.1. The table compares the previous machines regarding their performance based on the development profile sheet prepared by the British Institute of Brain Injured Children (BIBIC) against the Patterner Machine designed and developed at Middlesex laboratories. It also can be used for those who have gait related difficulties, by stimulating the normally dormant brain cells (90 % of the brains capacity), through physical activities which will lead to enhancing to over all performance by strengthening the development of motor control in the limbs of the patients. Further more, the output session of the Patterner Machine can be used to exercise joints of disabled people such as paraplegics, arthritic patients and individuals with long lasting injury which effects leg, arm, neck, and back portions of the body. Above all this Patterner Machine is designed to have input and output sessions where the child is encouraged to try to perform the learnt patterning techniques without any outside help. The machine is provided with a harness which will aid the patient carry out the output sessions. The input sessions are designed to be used after an assessment of the patient was made by the brain injury institute which in turn, will set up a program for the patient to follow, such as speed, step length, frequency (how often) and duration. A special care was taking to make sure that the automated machine is free of sharp edges and with low noise level.

Table 8.1: Comparison of the available Patterning Machines

Able to Perform:	Physio-Therapy Method	Physical therapy Patterner	Bed for Motor re-education	Physical Therapy Machine	The Ideal Mechatronic device
Basic Tasks	yes	yes	yes	yes	yes
Natural Patterning	no	no	no	no	yes
Creep on abdomen	no	no	no	no	yes
Crawl on Hands and Knees	no	no	no	no	yes
Walk with arms used for balance	no	no	no	no	yes
Free voluntary movement of limbs	no	no	no	no	yes
Aided output sessions	yes	no	no	no	yes
Used at home	yes	yes	no	yes	yes

The compression concluded that the Patterner Machine is an ideal machine to be used in the remedial process for brain injured children and especially for those with cerebral palsy who have never crept, crawled or walked.

### **8.1.6 Summary**

The following have been achieved :-

- Formulation of the most important patterning techniques.
- Formulation of final design specifications.
- Formulation of the optically sensed Patterner Machine position control strategy.
- Construction of one-axis prototype of the Patterner Machine.
- Development of a user friendly software program.
- Implementation and testing of the positional accuracy and repeatability accuracy of the system.
- Simulated performance analysis of the Patterner Machine.

## **8.2 FURTHER WORK**

### **8.2.1 Introduction**

The design of the Patterner Machine used in this research was based in theory on the techniques of Doman-Delacato (bench) method, but in practice the actual creep and crawl was the most important objective of this research. Although the aim of building one unit (a single axis) of the Patterner Machine was achieved, the machine can still be improved further.

### **8.2.2 Improvements to the Patterner Machine (unit I)**

Although only one unit was fully developed (a second unit is under construction), the other units would be identical to the developed unit. Further investigations regarding the stability of six units (put together) must be carried out once completed, as well as the

functional performance of the Patterner Machine as a whole unit. Although care was taken in selecting the most appropriate motor and gear box ratio, an improvement can still be made regarding the weight of the motor. The weight of the pulleys can be also reduced further by investigating the use of plastic pulleys. Another area of improvement would be the placement of the straps on the belt and a better all-purpose harness design which can be used to carry out the desired techniques.

### **8.2.3 Investigation into the Role of an Intelligent Patterner Machine**

Since the Patterner machine deals with brain injured children, the presence of a person to supervise the Patterner in Operation is essential, therefore the machine must be intelligent to stop as soon as the operator (supervisor) leaves the room. Once all other five prototype units are fully functional, investigations are required into implementing visual displays to monitor the child being patterned. A key pad with a visual display unit is strongly recommended.

### **8.2.4 Investigations into Safety**

After safety and reliability trials have been conducted in the laboratory for each individual unit. The next step is to put the whole device together once all other units are completed to test the full system in the home environment using volunteers children with mild brain injury to assess the functional performance of the Patterner Machine as one unit. The feedback and follow up gained from this stage must be used in the modification phase. An investigation into the incorporation of a pure mechanical clutch such as torque limiting or safety clutches is highly recommended.

### **8.2.5 Harness Design**

Body and walking harnesses are needed to support the patient during the input and output sessions. The function of the walking harness is to aid and support the brain injured child

during the input session of the patterning technique and also to support the child carry out movements during the output session. A body harness is intended to support 100 % of the child's weight during the input session and 15 to 20 % of the child's weight during the output session. Both types of harnesses are to be connected to the frame of the Patterner Machine via rails and must be designed to move in synchronism with other input and output movements of the brain injured child.

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## APPENDIX A

## APPENDIX A

### The Anthropometry Of Patterning Position [Doman, 66]

Dynamic anthropometry deals with dimensions of the patterning envelope needed by the patients as they perform their patterning. Unlike static body dimensions, dynamic measurements are made in the working positions.

The seven body measurements are taken in relation to the restriction imposed on the patients, i.e. straps. All measurements were made on a small group of primary schools and nurseries in the London area.

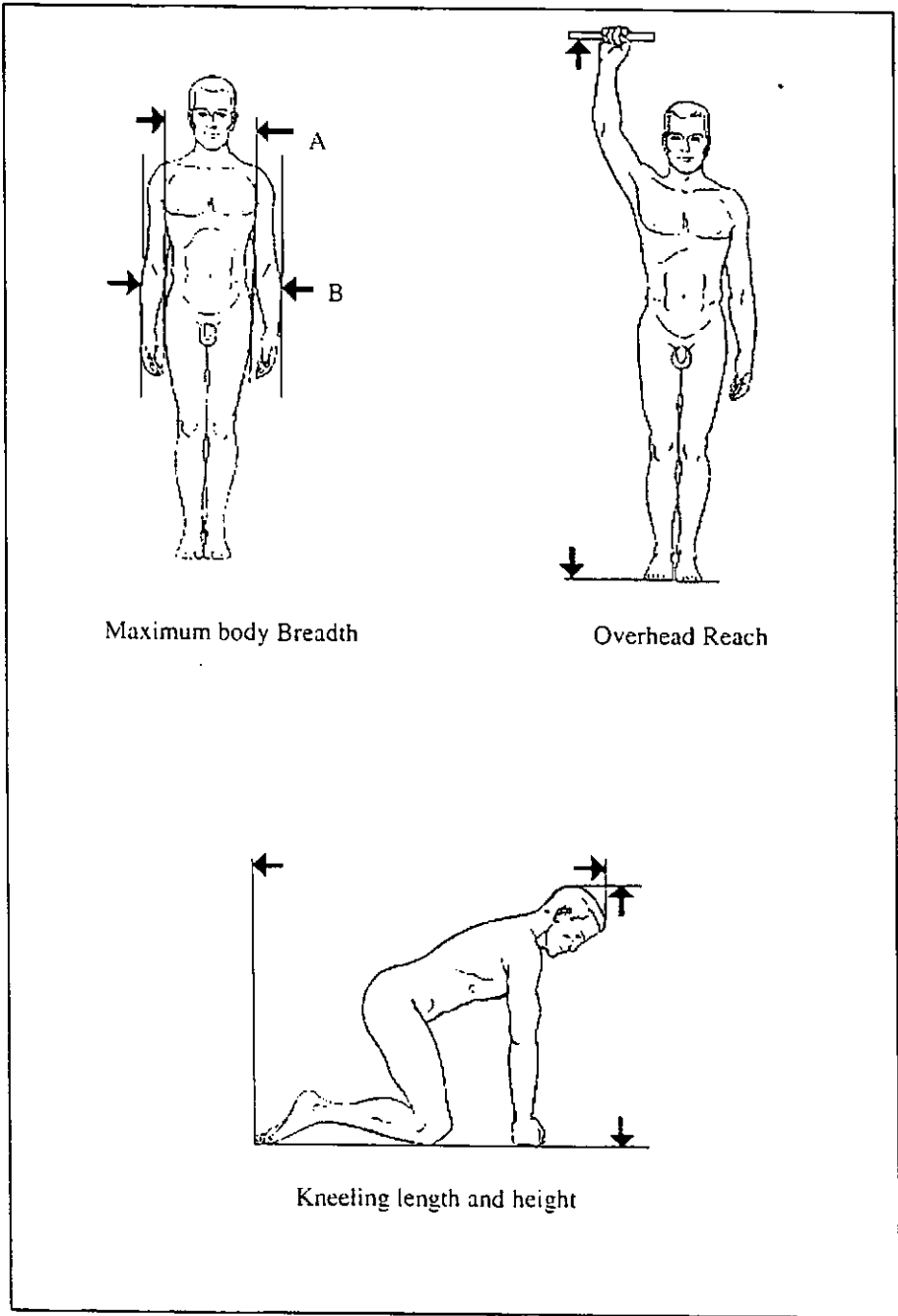
- a) Body Breadth: The subject stands erect with the arms hanging at sides
- b) Over head reach: The subject stands erect and raises a bar to the highest position attainable without strain.
- c) Kneeling length and height: The subject rests with knees and arms together, where length is measured from the rearmost point on the foot to the foremost point on the head and height is measured vertically from the floor to the highest point on the head.
- d) Crawling length and height: The subject kneels on knees and flattened palms, arms and thighs perpendicular to the floor, feet extended and spaced, body straight, head in line with the body. Length is measured from the rearmost point on the foot to the foremost point on the head and height is measured from the floor to the highest point on the head.
- e) Prone length and height: The subject lies prone where arms are extended and feet are together. Height is measured vertically from the floor to the highest point on the head. Length is measured horizontally from the rearmost point on the foot to the foremost point on the fists.
- f) Head Measurements: 1) head length, distance between the most anterior point on the forehead between the brow ridges and the most posterior point on the back of head, 2) head breadth, distance between the centres of the pupils, 3) head circumference, distance above the brow ridges.

- g) Upper and lower arms and legs: 1) lower arm, the distance between the start of wrist to the joint of the elbow, 2) Upper arm, the distance between the joint of the elbow to the joint of the shoulder, 3) lower leg, the distance between the start of ankle to the joint of the knee, 2) Upper leg, the distance between the joint of the knee to the joint of the hip.

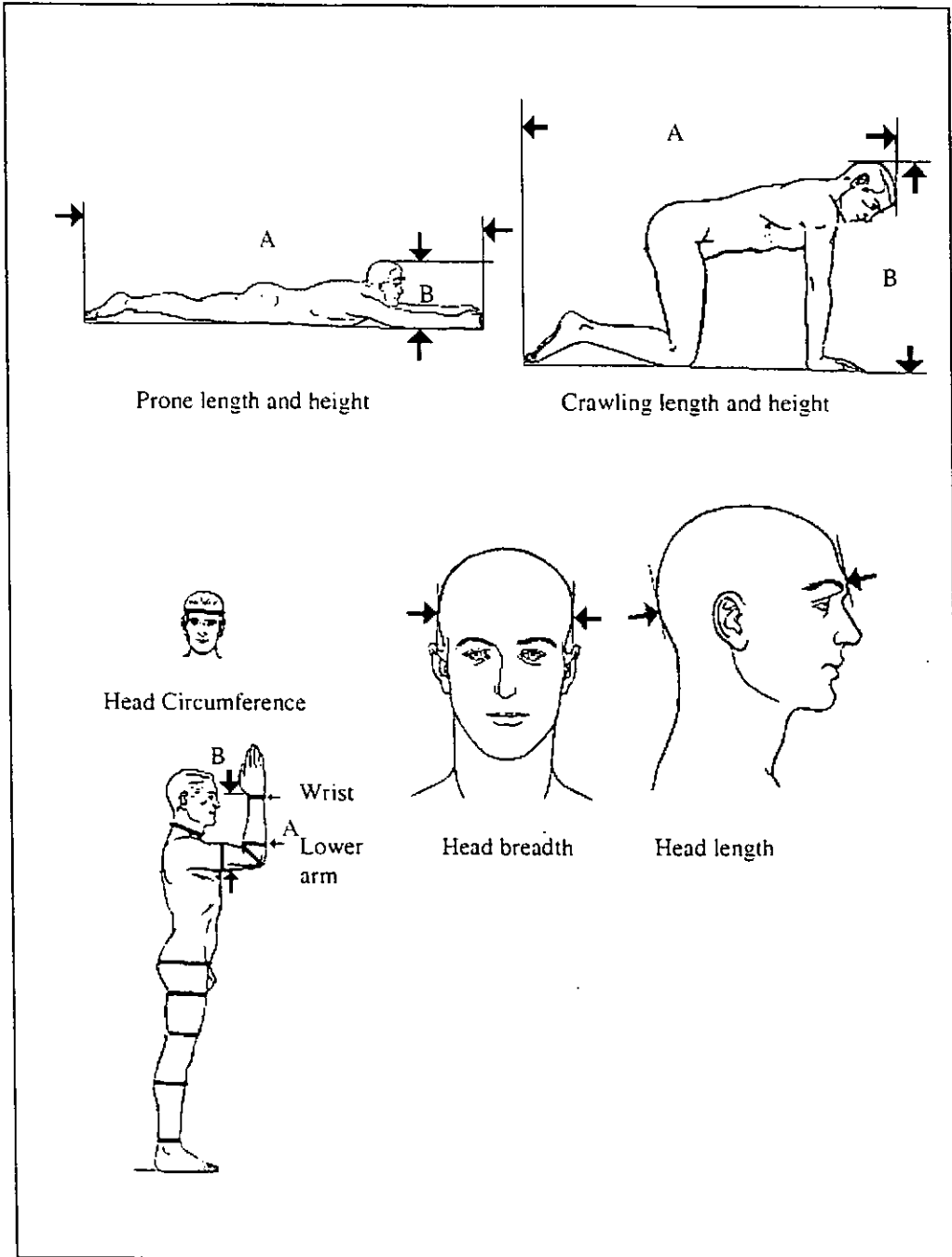
These measurements were used to determine the outer limits of the movement (stepping distance) of the Patterner Machine and for the placement of the straps. A change in any one dimension may alter the kinematics arrangement. These variations were therefore the prime reason for designing the Patterner Machine to a certain age group.











## APPENDIX B

## Appendix B

### Development Profile

The British Institute For Brain Injured Children believes that the Developmental Profile charts the developmental stages of normal children between birth and adulthood, in the areas of vision, hearing and understanding, touch, mobility, speech and manual competence. It also believes that every human being alive can be measured in this way, and the goal for every child is level 8, which should be the prime objective a child or a brain injured child to achieve.

# Evaluation

Vision

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Auditory

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Tactile

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Mobility

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Language

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Manual

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

**PROFILE CHANGES**

NAME OF CHILD \_\_\_\_\_

THE BRITISH INSTITUTE FOR BRAIN INJURED CHILDREN

PRESENT DATE \_\_\_\_\_

AGE AT INITIAL EVALUATION \_\_\_\_\_ AGE TODAY \_\_\_\_\_

# DEVELOPMENT PROFILE

DATE OF INITIAL EVALUATION \_\_\_\_\_

ASSESSMENT NUMBER \_\_\_\_\_

MONTHS SINCE LAST ASSESSMENT \_\_\_\_\_

SENSORY

EVALUATED BY \_\_\_\_\_ INDEX No: \_\_\_\_\_

MOTOR



VISUAL DEVELOPMENT	AUDITORY DEVELOPMENT	TACTILE DEVELOPMENT		TIME FRAME	LEVEL	MOBILITY	LANGUAGE	MANUAL DEVELOPMENT
		L	R					L
Able to read fluently with appropriate visual dominance	Understanding of complete vocabulary consistent with age level, using appropriate dominant ear	Able to identify by touch using appropriate dominant hand		PEER LEVEL IF OVER 6 YEARS	8	Able to move with co-ordination of age level, consistent with appropriate dominant foot	Able to converse appropriately at age level	Able to write at age level using appropriate dominant hand
Able to read single words	Able to understand complex sentences	Able to identify tiny objects by touch		6 YEARS	7	Able to hop, skip, jump and kick a ball	Able to speak in complete sentences	Able to write single words
Able to recognise symbols and letters within experience	Able to understand two stage commands and simple time concepts	Able to differentiate between similar objects		3 YEARS	6	Able to run in cross pattern	Able to speak in short sentences	Able to use both hands together purposefully
Able to recognise pictures within experience	Able to understand simple commands	Able to differentiate between dissimilar objects		18 MONTHS	5	Able to walk with arms no longer required for balance	Able to say two words together	Able to simultaneously oppose index finger and thumb of both hands
Able to focus both eyes simultaneously and appreciate the third dimension	Able to understand single words	Awareness of the third dimension		12 MONTHS	4	Able to walk with arms used for balance	Able to say single words	Able to oppose index finger and thumb of either hand
Able to see details within an outline	Able to recognise meaningful sounds	Able to react to light touch		6 MONTHS	3	Able to crawl in cross pattern on hands & knees	Able to make sounds; culminating in communicative sounds	Able to grasp objects purposefully
Able to see outline	Vital response to threatening sounds	Awareness of vital sensation		3 MONTHS	2	Able to creep in cross pattern on abdomen	Able to respond by crying to vital threats	Able to release in response to a vital stimulus
Reflexive response to light	Reflexive response to loud noise	Babinski reflex		BIRTH	1	Free voluntary movement of limbs	Able to cry	Reflexive grasping with hands



## APPENDIX C





### Appendix C

The following Figures C1 and C2 show the actual set-up of the control system for one unit of the Patterner Machine and the circuit digram showing the interconnections between the controller, 1000 quadrature encoder and the motor driver for the permanent magnet DC motor.

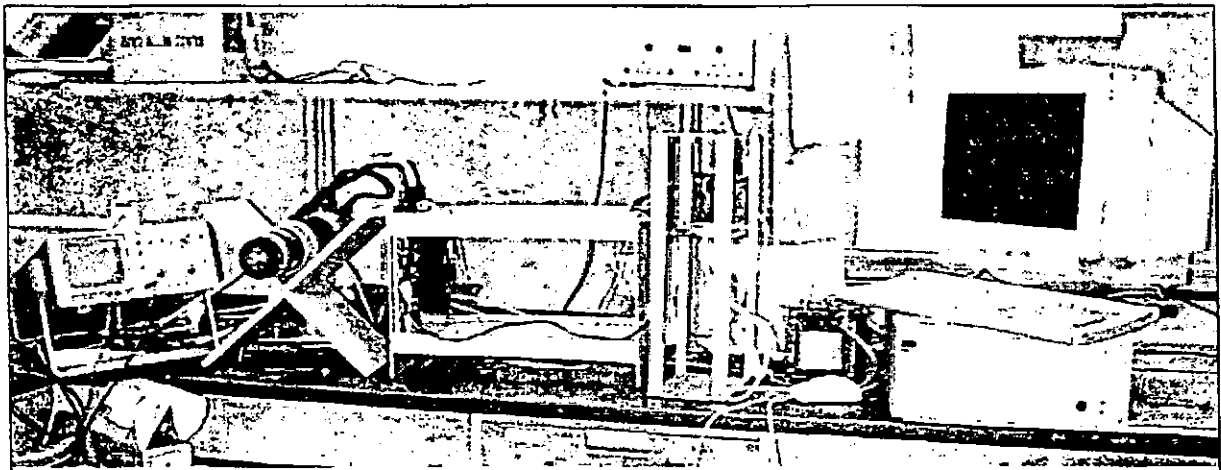


Figure C1. Actual set-up used to control the Patterner Machine motor

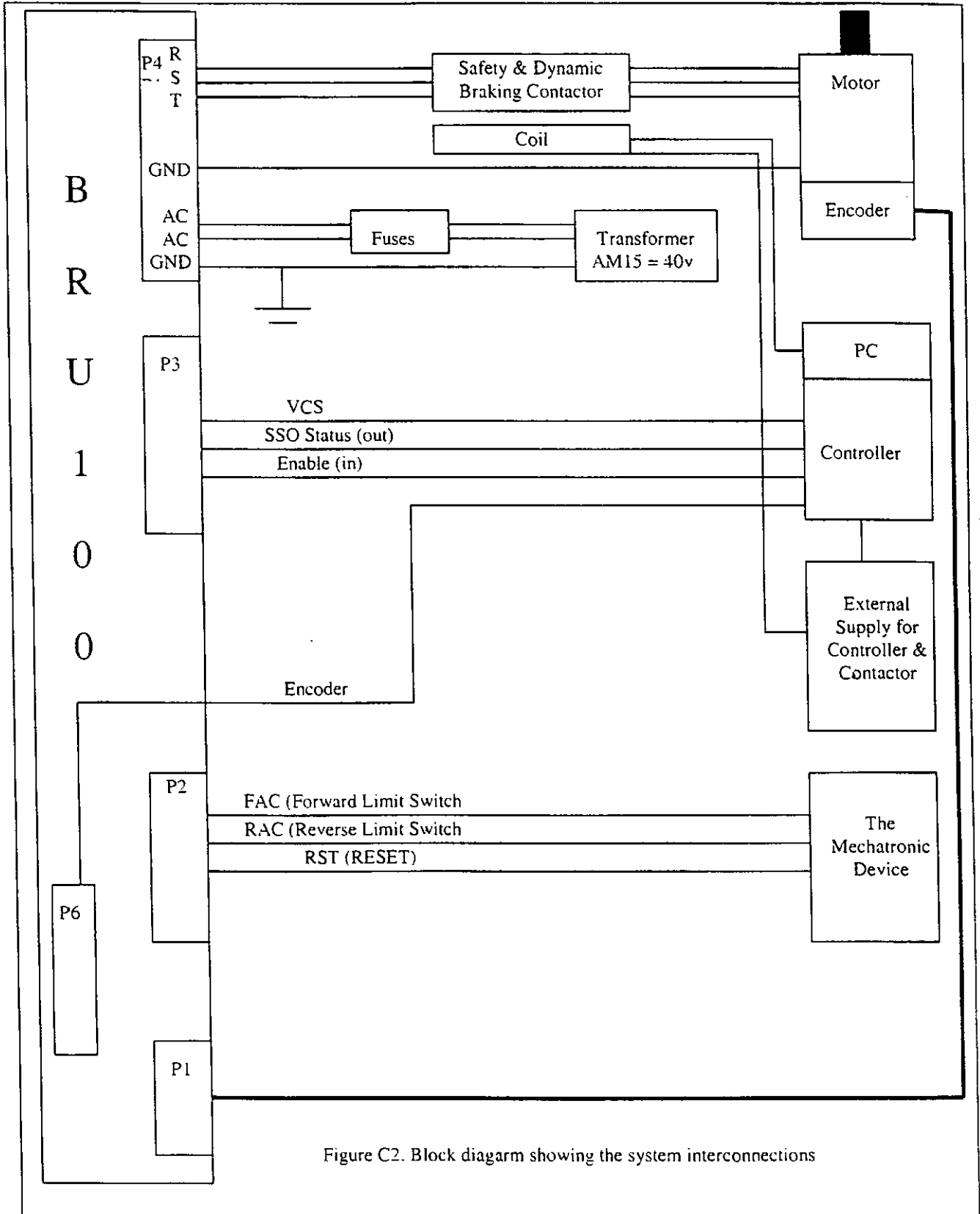


Figure C2. Block diagram showing the system interconnections

## APPENDIX D

## Appendix D

The following is the procedure used to select a suitable motor, gearbox and drive for the Patterning Machine. The selection of the above listed items was based on an acceleration required at the gearbox output shaft of  $30 \text{ rads/s}^2$  with a maximum velocity of  $3 \text{ rads/s}$ . The load on each unit was assumed to be approximately  $20 \text{ kg}$  with a reflected inertia of  $0.36 \text{ kgm}^2$ . At output shaft of gearbox, the peak torque required was  $10.8 \text{ Nm}$  and the rms torque was  $6.7 \text{ Nm}$ .

### SELECTED SYSTEM

Amplifier	AM15	
Motor	3633-3Y	(Manufacturer: Electro-Craft)
Gearhead	BGT800-30	30:1

ACTUATOR TYPE BELT OR WEB

**Motor -- 3633-3Y**

	<u>LOAD REQUIREMENT</u>	<u>MOTOR RATING /UNITS</u>	
RMS Torque	0.575	1.56	
Nm			
Peak Torque	1.08	6.61	
Nm			
RMS Velocity	853.75		rev/m
Peak Velocity	859.44	4001.16	rpm
Winding temperature	53.48	125.00	C°
Inertia Ratio (Min)	0.772		Nm
Inertia Ratio (Max)	0.772		Nm

Reflected Inertia (Min)	2.47	E <sup>-4</sup>	3.20E <sup>-4</sup>	kg m <sup>2</sup>
Reflected Inertia (Max)	2.47	E <sup>-4</sup>	3.20E <sup>-4</sup>	kg m <sup>2</sup>
Ambient temperature	40.00			C°
Average Current	2.91		8.06	A
Peak Current	5.58		30.00	A
Average Shaft Power	50.87			W
Peak Shaft Power	51.47		2514.00	W

### Amplifier -- AM15 (Electro-Craft)

	<u>LOAD REQUIREMENT</u>	<u>AMPLIF. RATING /UNITS</u>	
Average Current	2.91	8.00	A
Peak Current	5.58	15.00	A
Average Dump Power	0.000	20.00	W
Peak Bus Volts Needed	20.88	56.57	V
Critical Dump Power	0.000		W
Critical Dump Time	0.000		s

### GearheadBGT800~30 30:1 (Elecro-Craft)

	<u>LOAD REQUIREMENT</u>	<u>GEARHEAD /UNITS</u>	
<u>RATING</u>			
RMS Torque	5.08	46.00	Nm
Peak Torque	11.56	90.00	Nm
Power Loss	33.11		W
Output Power Watts	14.90	1.93 E 4	
Peak Velocity	859.44	4000.00	rev/m



**ACTUATOR BELT DRIVE DATA**

Inertia 1	8.52	E-3	kg m <sup>2</sup>
Drive Radius	100.00		mm
Inertia 2	0.000		kg m <sup>2</sup>
Radius	100.00		mm
Inertia 3	0.000		kg m <sup>2</sup>
Radius	100.00		mm
Inertia 4	0.000		kg m <sup>2</sup>
Radius	100.00		mm
Belt Mass	1.00		kg
Losses	5.00		Nm
Inclination	0.000		
Temperature	40.00		C°
Table Mass	40.00		kg
Friction	40.00		Nm

**TRANSMISSION****TRANSMISSION 1 DATA**

Ratio	1.00		
Coupling Inertia	0.000		kg m <sup>2</sup>
Efficiency	100.00		%
Friction Torque	0.000		Nm
First loss coeff.	0.000		
Second loss coeff.	0.000		

**TRANSMISSION 2 DATA**

Ratio	1.00		
Coupling Inertia	0.000		kg m <sup>2</sup>

Efficiency	100.00	%
Friction Torque	0.000	Nm
First loss coeff.	0.000	
Second loss coeff.	0.000	

**Transmission Stage 1****Loading**

RMS Torque	5.08	kg m <sup>2</sup>
Peak Torque	11.56	kg m <sup>2</sup>
Power Loss	0.000	kg

**Transmission Stage 2****Loading**

RMS Torque	5.08	kg m <sup>2</sup>
Peak Torque	11.56	kg m <sup>2</sup>
Power Loss	0.000	kg

**DYNAMICS SEGMENT 1**

Peak Segment Torque	1.08	N m
RMS Segment Torque	0.980	N m
Acceleration Torque	0.510	N m
Friction Torque	0.470	N m
Gravitational Torque	0.000	N m
External Thrust Torque	0.000	N m
Inertia Ratio	0.772	
Current	4.42	A
Motor Terminal Volts	20.88	V
Peak Shaft Power	0.000	W
Dump Power	0.000	W

**Motor**

Initial Velocity	0.000	rev/min
Final Velocity	859.44	rev/min
Acceleration	8594.37	rev/min/s
Displacement	0.716	Rev

**Load**

Initial Velocity	0.000	m/s
------------------	-------	-----

Final Velocity	0.300		m/s
Acceleration	3.00		m/s <sup>2</sup>
Displacement	1.50	E <sup>-2</sup>	m
Load	0.000		kg
Thrust	0.000		N
Time	0.100		s

## DYNAMICS SEGMENT 2

Peak Segment Torque	0.572	N m
RMS Segment Torque	0.572	N m
Acceleration Torque	0.000	N m
Friction Torque	0.572	N m
Gravitational Torque	0.000	N m
External Thrust Torque	0.000	N m
Inertia Ratio	0.772	
Current	2.56	A
Motor Terminal Volts	19.65	V
Peak Shaft Power	51.47	W
Dump Power	0.000	W

### **Motor**

Initial Velocity	859.44	rev/min
Final Velocity	859.44	rev/min
Acceleration	0.000	rev/min
Displacement	141.81	rev

### **Load**

Initial Velocity	0.300	m/s
------------------	-------	-----

Final Velocity	0.300	m/s
Acceleration	0.000	m/s <sup>2</sup>
Displacement	2.97	m
Load	0.000	kg
Thrust	0.000	N
Time	9.90	s

### DYNAMICS SEGMENT 3

Peak Segment Torque	0.157	N m
RMS Segment Torque	-4.73	E <sup>-2</sup> N m
Acceleration Torque	-0.510	N m
Friction Torque	0.463	N m
Gravitational Torque	0.000	N m
External Thrust Torque	0.000	N m
Inertia Ratio	0.772	
Current	-0.211	A
Motor Terminal Volts	0.000	V
Peak Shaft Power	4.26	W
Dump Power	0.000	W

#### **Motor**

Initial Velocity	859.44	rev/min
Final Velocity	0.000	rev/min
Acceleration	-8594.37	rev/min/s
Displacement	0.716	rev

#### **Load**

Initial Velocity	0.300	m/s
------------------	-------	-----

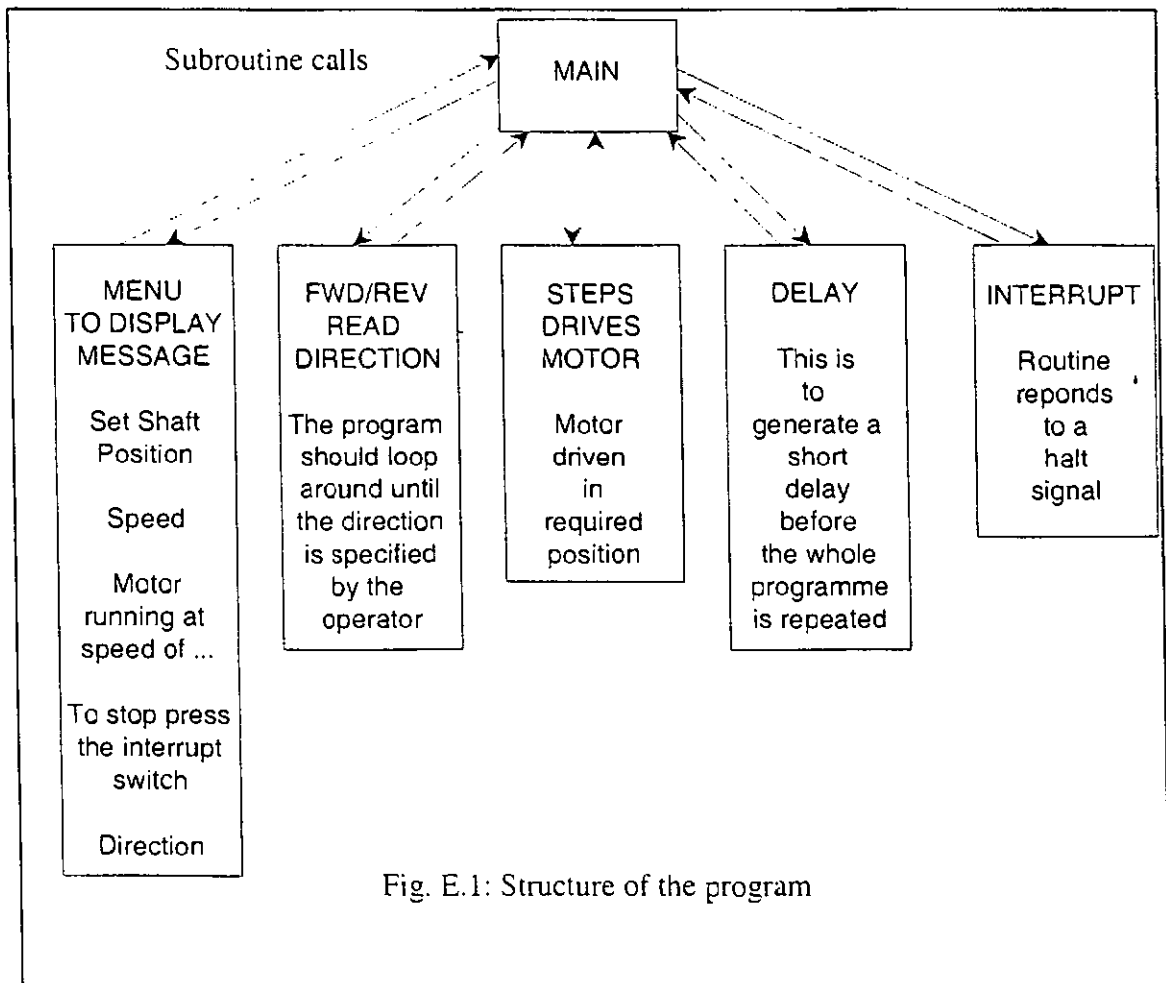
---

Final Velocity	0.000	m/s
Acceleration	-3.00	$\text{m/s}^2$
Displacement	1.50 E <sup>-2</sup>	m
Load	0.000	kg
Thrust	0.000	N
Time	0.100	s

## APPENDIX E

## Appendix E

This software program is a user friendly program. It was designed in away an ordinary person can operate it with no prior knowledge of how the program work. Common every day language was used to follow instructions and procedures. The program is written in customised programming language called CTERM. Cterm is a combination of two languages, namely Visual Basic and C language. The program is divided into two main sections, 1) the configuration file program which will not be accessible to the user and 2) the executable file which in turn is divided into two subsections: 1) main program and 2) twenty two subroutine programs.



```

REM -----
REM This Program is written by Mr. A. R. Lasebae.
REM This is the Final version of the program which was completed in October 1997.
REM File name: rev.mnt
REM Optimised Control Ltd
REM -----
REM Program to demonstrate use of the keypad to cause
REM the motor to move a desired index distance in REVS.
RESET[0,1,2] REM Reset all motion parameters to default values
GOSUB initialise
GOSUB menue
REM GOSUB main
GOSUB main_loop
END

#initialise REM initialise variables used in program
REM This subroutine sets up various parameters when program starts
indexF_length = 0
indexB_length = 0
lindex = 0
finde = 3000 REM Maximum number of revolutions the motor can turn
oursp=0
count= 0
jog_sp = 200 REM Default jog speed in manual mode
BEEPOFF REM Turn off automatic keyboard beep
KEYS "" REM enable keyboard with default layout
RETURN

#menu

LOOP
CLS
PRINT" This device is used for patterning brain injured children"
PRINT" Choose the type of Patterning you would like this device to"
PRINT" perform by choosing one of the following"
Print""
Print"      A) CREEPING "
PRINT""
Print"      B) CRAWLING "
Print""
Print"      C) WALKING "

Key = 0 REM Wait for a key to be pressed
WHILE Key = 0

```



```

    Key = INKEY
    IF Key = 'A' THEN BEEP : GOSUB creep
    IF Key = 'B' THEN BEEP : GOSUB crawl
    IF Key = 'C' THEN BEEP : GOSUB walk
  ENDW
ENDL
RETURN

#main

LOOP
CLS :REM Clear the screen

REM Setting the position of the motor shaft
PRINT" Do you wish to set the position of the motor shaft? Y or N"
Key = 0
REM Wait for a key to be pressed
WHILE Key = 0
  Key = INKEY :REM read keyboard
  IF KEY = 'Y' THEN GOSUB manual
  IF KEY = 'N' THEN GOSUB main_loop
ENDW
ENDL
RETURN

#main_loop

REM This program is the main program loop, it prints up a menu for entering
REM required information to run the program
a= _false
REPEAT
CLS
PRINT " NOW, PLEASE ENTER the following parameters"
LINE 2,"Enter Required number of REVOLUTIONS "
LOCATE 5,3 : REM put cursor at column five line three
INPUT indexF_length REM USING 4,2 input statement uses formatted input
LINE 3, " The BEIT moves this number of REV. "; (indexF_length/30)
LOCATE 22,3
IF indexF_length > findex THEN GOSUB stop
REPEAT
LINE 4,"Enter speed in revs (not greater than 30 rev and not less than 1 rev"
BEEPON
LOCATE 5,5
INPUT oursp REM USING 2,2 input statement uses formatted input
SPEED= oursp

```

```

BEEPOFF
UNTIL SPEED >= 0.50 AND SPEED <= 30
PRINT "      The speed in revs/sec is "; SPEED

MOVER = indexF_length: GO : REM move relative command AND start motion
BEEP
count = count + indexF_length REM accumulate revs moved
IF count > findex THEN STOP

GOSUB readFE
  IF count >= findex THEN a = _true
UNTIL a
IF a = _true THEN GOSUB reverse
REM ENDL REM go back to start of loop for next motion
RETURN

REM This subroutine is the manual mode allowing movement of belt back and forth

#manual

RESET[0,1,2]
jog_sp = 0
KEYS ""
REM -----
  CLS
  PRINT " NOW you are in the MANUAL MODE to set the position of the Shaft"
  PRINT " Please :"
REPEAT
  LINE 3,"Enter jog speed in revs "
  LOCATE 5,4
  INPUT jog_sp USING 2,1 REM input statement uses formatted input xxx.x
UNTIL jog_sp >= 0.50 AND jog_sp <= 30
PRINT "      The Jog speed in revs/sec is "; jog_sp

PRINT "NOW to move the SHAFT - Please Press"
PRINT "(R) to move right and (L) to move left (S) to stop motion & (E) to exit"
REM This moves motor back and forth the arrow keys < and >
REM When key is pressed and held it moves to the direction indicated
  REPEAT
    key = INKEY
    IF KEY = 'R' DO JOG = - jog_sp
    ELSE IF KEY = 'L' DO JOG = jog_sp
    ELSE IF KEY = 'S' DO STOP REM Stop motion of motor
    ENDIF
  ENDIF

```

```

    ENDIF
    UNTIL key = 'E'
    REM Print the following error, demand and position
    PRINT FOLERR.0;DEMAND.0;POS.0 : BOL
    WAIT = 1000      : REM Wait 100 milliseconds
rem ENDL
RETURN

#reverse

CLS :REM Clear the screen
REM Print up screen requesting user to enter move distance
BEEP
count = findex
b = _false
REPEAT
CLS
LINE 1,"Enter NUMBER of REVOLUTIONS to move motor back "
LOCATE 5,2 : REM put cursor at column five line 2
INPUT indexB_length USING 4,2 REM input statement uses formatted input xxx.x
PRINT " The distance to move is "; indexB_length
IF indexB_length > findex THEN GOSUB stop
REPEAT
LINE 3,"Enter speed in revs to move back "
LOCATE 5,4
INPUT oursp USING 2,2 REM input statement uses formatted input xxx.x
SPEED= oursp
UNTIL SPEED >= 0.50 AND SPEED <= 30
PRINT " The speed in revs/sec is "; SPEED
REM move relative command AND start REVERSE motion
MOVER = -(indexB_length) : GO :
count = count - indexB_length REM Go back accumulated revs moved
GOSUB readFE
IF count <= lindex THEN b = _true
UNTIL b
IF b = _true THEN GOSUB main_loop
RETURN

#readFE

REM Read the following error and position until the motor stops.
REPEAT
PRINT FE; DEMAND; POS; count: : BOL
WAIT = 100
UNTIL IDLE =_true

```

```
RETURN
```

```
#stop
```

```
CLS
```

```
REM Error handling routine called by system when STOP input
```

```
REM is Asserted. Subroutine prints message on operator screen,
```

```
REM then returns to main program
```

```
LOOP
```

```
PRINT " SORRY, YOU CAN NOT EXCEED THE LIMITS OF THE DEVICE"
```

```
PRINT " PLEASE press (E) to re-run program"
```

```
KEY = 0
```

```
WHILE KEY = 0
```

```
KEY = INKEY
```

```
IF KEY = 'E' THEN GOSUB run
```

```
ENDW
```

```
ENDL
```

```
RETURN
```

```
#run
```

```
CLS
```

```
REM When error is made during processing, this subroutine runs the
```

```
REM program automatically without shutting off the power
```

```
RESET[0,1,2] REM reset controller
```

```
CANCEL REM Cancel error and re-run program
```

```
run REM and re-execute the program
```

```
RETURN
```

```
#creep
```

```
LOOP
```

```
CLS
```

```
PRINT" There are two types of creeping patternings"
```

```
PRINT" please enter the patterning action you require"
```

```
PRINT" 1) Homolateral"
```

```
PRINT" 2) Cross Pattern"
```

```
Key = 0
```

```
WHILE Key = 0
```

```
Key = INKEY
```

```
IF Key = '1' THEN BEEP : GOSUB hcreep
```

```
IF Key = '2' THEN BEEP : GOSUB ccreep
```

```
ENDW
```

```
ENDL
RETURN
```

```
#hcreep
```

```
LOOP
CLS
PRINT" Before starting HOMOLATERAL CREEP patterning,"
PRINT" PLEASE PUT the child in the PRONE position on units 2,3,4 & 5"
PRINT" to see if you need to adjust the units"
PRINT" IF you do PLEASE PRESS 'Y' otherwise press 'N'"
Key = 0
WHILE Key = 0
KEY = INKEY
IF KEY = 'Y' THEN GOSUB manual
IF KEY = 'N' THEN GOSUB hcreep1
ENDW
ENDL
RETURN
```

```
#hcreep1
```

```
LOOP
CLS
PRINT" To Preforme HOMOLATERAL creep PLEASE ensure the following"
PRINT" Use UNITS 2,3,4 & 5 "
PRINT" Fasten the child's LEFT foot to unit 2 and RIGHT foot to unit 4"
PRINT" Fasten the child's LEFT arm to unit 3 and RIGHT arm to unit 5"
PRINT" Make sure the harness is fastened around the child's TORSO"
PRINT" If you finshed please prees (F)"
Key = 0
WHILE Key = 0
key = INKEY
IF KEY = 'F' THEN BEEP : GOSUB main_loop
ENDW
ENDL
RETURN
```

```
#ccreep
```

```
LOOP
CLS
PRINT" Before starting CROSS CREEP patterning,"
PRINT" PLEASE PUT the child in the PRONE position on units 1,2,3,4,5 & 6"
PRINT" to see if you need to adjust the units"
```

PRINT" IF you do PLEASE PRESS 'Y' otherwise press 'N'"

```
Key = 0
WHILE Key = 0
KEY = INKEY
IF KEY = 'Y' THEN GOSUB manual
IF KEY = 'N' THEN GOSUB ccreep1
ENDW
ENDL
RETURN
```

#ccreep1

```
LOOP
CLS
PRINT" To Preforme Cross Creeping PLEASE ensure the following"
PRINT" Use UNITS 1,2,3,4,5 & 6 "
PRINT" Fasten the child's LEFT foot to unit 2 and RIGHT to unit 5"
PRINT" Fasten the child's LEFT arm to unit 1 and RIGHT arm to unit 6"
PRINT" Fasten the child's chest and torso to units 3 & 4"
PRINT" Make sure the harness is fastened around the child's chest and torso"
PRINT" If you finshed please prees (F)"
Key = 0
WHILE Key = 0
key = INKEY
IF KEY = 'F' THEN BEEP : GOSUB main_loop
ENDW
ENDL
RETURN
#crawl
```

```
LOOP
CLS
PRINT" There are two types of crawling pattermings"
PRINT" please enter the patterning action you require"
PRINT" 1) Homolateral"
PRINT" 2) Cross Pattern"
Key = 0
WHILE Key = 0
Key = INKEY
IF Key = '1' THEN BEEP : GOSUB hcrawl
IF Key = '2' THEN BEEP : GOSUB ccrawl
ENDW
ENDL
RETURN
```

```
#ccrawl
```

```
LOOP
CLS
PRINT" Before starting CROSS CRAWL patterning,"
PRINT" PLEASE PUT the child on his knees and hands position on units 2,3,4 & 5"
PRINT" to see if you need to adjust the units"
PRINT" IF you do PLEASE PRESS 'Y' otherwise press 'N'"
Key = 0
WHILE Key = 0
KEY = INKEY
IF KEY = 'Y' THEN GOSUB manual
IF KEY = 'N' THEN GOSUB ccrawl1
ENDW
ENDL
RETURN
```

```
#ccrawl1
```

```
LOOP
CLS
PRINT" To Preforme CROSS Crawl PLEASE ensure the following"
PRINT" Use UNITS 2,3,4 & 5 "
PRINT" Fasten the child's LEFT foot and knee to unit 3"
PRINT" and RIGHT foot and knee to unit 4"
PRINT" Fasten the child's LEFT hand to unit 2"
PRINT" and RIGHT hand to unit 5"
PRINT" Make sure the harness is fastened around the child's body and torso"
PRINT" If you finshed please prees (F)"
Key = 0
WHILE Key = 0
key = INKEY
IF KEY = 'F' THEN BEEP : GOSUB main_loop
ENDW
ENDL
RETURN
```

```
#hcrawl
```

```
LOOP
CLS
PRINT" Before starting HOMOLATERAL CRAWL patterning,"
PRINT" PLEASE PUT the child on his knees and hands position on units 2,3,4, & 5"
PRINT" to see if you need to adjust the units"
PRINT" IF you do PLEASE PRESS 'Y' otherwise press 'N'"
```

```

Key = 0
WHILE Key = 0
KEY = INKEY
IF KEY = 'Y' THEN GOSUB manual
IF KEY = 'N' THEN GOSUB hcrawl1
ENDW
ENDL
RETURN

#hcrawl1

LOOP
CLS
PRINT" To Preforme HOMOLATERAL Crawl PLEASE ensure the following"
PRINT" Use UNITS 2,3,4 & 5 "
PRINT" Fasten the child's LEFT foot and knee to unit 3"
PRINT" and RIGHT foot and knee to unit 4"
PRINT" Fasten the child's LEFT hand to unit 2"
PRINT" and RIGHT hand to unit 5"
PRINT" Make sure the harness is fastened around the child's body and torso"
PRINT" If you finshed please prees (F)"
Key = 0
  WHILE Key = 0
    key = INKEY
    IF KEY = 'F' THEN BEEP : GOSUB main_loop
  ENDW
ENDL
RETURN

#walk

LOOP
CLS
PRINT" Before starting WALK patterning,"
PRINT" PLEASE PUT the child in the standing up position on units 3 & 4"
PRINT" to see if you need to adjust the units"
PRINT" IF you do PLEASE PRESS 'Y' otherwise press 'N'"
Key = 0
  WHILE Key = 0
    KEY = INKEY
    IF KEY = 'Y' THEN GOSUB manual
    IF KEY = 'N' THEN GOSUB walk1
  ENDW
ENDL
RETURN

```



```
#walkI
```

```
LOOP
```

```
CLS
```

```
PRINT" To Preforme walking PLEASE ensure the following"
```

```
PRINT" Use UNITS 3 & 4 "
```

```
PRINT" Fasten the child's LEFT foot to unit 3 and RIGHT FOOT to unit 4"
```

```
PRINT" Make sure the harness is fastened around the child's shoulders"
```

```
PRINT" If you finshed please prees (F)"
```

```
Key = 0
```

```
WHILE Key = 0
```

```
    key = INKEY
```

```
    IF KEY = F THEN BEEP : GOSUB main_loop
```

```
ENDW
```

```
ENDL
```

```
RETURN
```

## APPENDIX F

## APPENDIX F

**Appendix F:**

Tables F1 to F4 list the actual data for the movement of the right foot of a child. The foot was divided into four segments. The high-speed video camera recorded all the necessary movements of the foot. The foot was divided into four segments. Each segment was highlighted and its data was analysed using a software program called Optimas. Table F5 lists the measurements of arm movements. Data in Tables F1 to F4, positions were measured in meters, velocity in m/s and time in seconds. Data in Table F5, time in seconds, position in millimetres, velocity in m/s and acceleration in  $\text{m/s}^2$ .

Table F1: Segment I of the foot

Direction	Distance	X Pos.	Y Pos.	Velocity	Time
0	0	12.037	6.129	0	0
316.627	0.61	12.48	5.711	0.61	1
305.043	1.26	12.747	5.117	0.63	2
300.769	2.169	13.13	4.293	0.723	3
305.48	2.719	13.576	3.97	0.68	4
302.147	3.219	13.699	3.485	0.644	5
300.163	3.613	13.796	3.104	0.602	6
299.322	3.942	13.91	2.795	0.563	7
298.238	4.164	13.945	2.577	0.52	8
297.931	4.24	13.96	2.502	0.471	9
297.879	4.316	13.993	2.433	0.432	10
300.598	4.531	14.205	2.464	0.412	11
301.016	4.572	14.246	2.456	0.381	12
310.084	5.492	15.164	2.414	0.422	13
310.245	5.525	15.194	2.4	0.395	14
310.355	5.539	15.208	2.398	0.369	15
310.371	5.554	15.218	2.387	0.347	16
310.464	5.572	15.235	2.38	0.328	17
310.501	5.577	15.234	2.386	0.31	18
309.374	5.777	15.049	2.46	0.304	19
300.721	6.635	14.191	2.504	0.332	20
301.876	6.72	14.263	2.551	0.32	21
303.034	6.816	14.311	2.633	0.31	22
304.649	6.951	14.369	2.755	0.302	23
305.796	7.066	14.389	2.868	0.294	24
307.263	7.208	14.412	3.008	0.288	25
308.987	7.368	14.435	3.167	0.283	26
310.275	7.481	14.453	3.278	0.277	27
311.408	7.591	14.454	3.388	0.271	28
312.805	7.702	14.475	3.497	0.266	29
314.022	7.793	14.495	3.586	0.26	30
315.076	7.876	14.504	3.669	0.254	31
316.317	7.967	14.52	3.758	0.249	32
318.162	8.112	14.523	3.904	0.246	33
320.015	8.227	14.563	4.011	0.242	34
323.708	8.45	14.635	4.222	0.241	35
326.137	8.592	14.676	4.358	0.239	36
331.346	8.882	14.791	4.625	0.24	37
337.113	9.198	14.913	4.915	0.242	38
344.056	9.577	14.976	5.29	0.246	39
357.196	10.298	14.817	5.993	0.257	40
18.437	11.685	15.4	7.25	0.285	41
24.78	13.03	16.405	8.145	0.31	42
28.864	15.384	18.279	9.57	0.358	43

Table F2: Segment II of the Foot

Direction	Distance	X Pos.	Y Pos.	Velocity	Time
0	0	9.029	4.608	0	0
317.628	0.461	9.369	4.298	0.461	1
300.515	1.002	9.518	3.777	0.501	2
310.199	1.565	9.99	3.47	0.522	3
311.863	1.792	10.171	3.333	0.448	4
310.488	2.396	10.531	2.848	0.479	5
313.103	2.704	10.806	2.71	0.451	6
312.763	2.905	10.931	2.552	0.415	7
310.481	3.017	10.849	2.475	0.377	8
309.1	3.122	10.848	2.37	0.347	9
308.731	3.172	10.863	2.322	0.317	10
309.143	3.194	10.88	2.333	0.29	11
309.408	3.21	10.897	2.335	0.267	12
308.917	3.256	10.901	2.289	0.25	13
309.877	3.307	10.933	2.329	0.236	14
312.099	3.473	10.938	2.495	0.232	15
310.757	3.782	10.691	2.68	0.236	16
313.086	3.886	10.757	2.761	0.229	17
314.68	3.956	10.804	2.813	0.22	18
318.233	4.374	11.197	2.672	0.23	19
321.942	4.562	11.306	2.825	0.228	20
326.033	4.768	11.426	2.993	0.227	21
329.549	4.953	11.47	3.173	0.225	22
334.782	5.221	11.515	3.437	0.227	23
339.294	5.441	11.555	3.653	0.227	24
344.683	5.697	11.593	3.906	0.228	25
350.812	5.98	11.642	4.186	0.23	26
355.154	6.182	11.678	4.384	0.229	27
358.76	6.353	11.719	4.55	0.227	28
2.816	6.551	11.764	4.743	0.226	29
5.744	6.701	11.803	4.887	0.223	30
8.194	6.829	11.834	5.012	0.22	31
11.681	7.018	11.874	5.196	0.219	32
15.69	7.258	11.942	5.427	0.22	33
18.838	7.486	12.036	5.634	0.22	34
22.65	7.812	12.183	5.925	0.223	35
24.992	8.03	12.277	6.122	0.223	36
28.847	8.498	12.512	6.527	0.23	37
32.229	9.013	12.775	6.97	0.237	38
6.536	11.783	14.976	5.29	0.302	39
41.317	15.322	13.421	8.469	0.383	40
44.103	16.853	14.304	9.721	0.411	41
43.525	18.559	15.59	10.84	0.442	42
28.207	21.532	18.279	9.57	0.501	43

Table F3: Segment III of the Foot

Direction	Distance	X Pos.	Y Pos.	Velocity	Time
0	0	6.643	3.648	0	0
315.04	0.475	6.979	3.313	0.475	1
300.736	0.826	7.047	2.968	0.413	2
315.999	1.189	7.405	2.912	0.396	3
319.706	1.462	7.652	2.793	0.366	4
318.751	1.601	7.74	2.686	0.32	5
315.622	1.721	7.749	2.566	0.287	6
319.523	1.915	7.941	2.541	0.274	7
318.114	1.969	7.938	2.487	0.246	8
318.769	1.991	7.959	2.495	0.221	9
315.794	2.102	7.85	2.474	0.21	10
316.482	2.123	7.866	2.487	0.193	11
317.627	2.166	7.908	2.494	0.18	12
319.51	2.222	7.941	2.54	0.171	13
321.9	2.293	7.986	2.596	0.164	14
327.426	2.466	8.119	2.705	0.164	15
332.151	2.617	8.147	2.854	0.164	16
335.922	2.731	8.211	2.948	0.161	17
340.619	2.932	8.393	3.033	0.163	18
348.023	3.172	8.466	3.262	0.167	19
356.588	3.459	8.554	3.534	0.173	20
4.532	3.726	8.571	3.801	0.177	21
12.799	4.031	8.631	4.1	0.183	22
18.374	4.362	8.82	4.372	0.19	23
24.764	4.672	8.873	4.677	0.195	24
31.072	5.052	8.963	5.047	0.202	25
34.691	5.46	9.171	5.398	0.21	26
37.572	5.705	9.227	5.637	0.211	27
40.016	5.958	9.3	5.879	0.213	28
41.445	6.223	9.43	6.11	0.215	29
42.509	6.412	9.513	6.279	0.214	30
43.525	6.568	9.566	6.425	0.212	31
44.721	6.786	9.65	6.627	0.212	32
46.294	7.125	9.786	6.937	0.216	33
47.186	7.408	9.921	7.186	0.218	34
48.254	7.833	10.131	7.557	0.224	35
48.859	8.151	10.295	7.829	0.226	36
49.583	8.735	10.617	8.316	0.236	37
50.02	9.419	11.02	8.868	0.248	38
50.397	10.249	11.514	9.536	0.263	39
51.618	11.589	12.212	10.68	0.29	40
38.402	13.89	14.304	9.721	0.339	41
38.793	15.596	15.59	10.84	0.371	42
26.97	18.569	18.279	9.57	0.432	43

Table 4: Segment VI of the Foot

Direction	Distance	X Pos.	Y Pos.	Velocity	Time
0	0	4.818	2.776	0	0
317.014	0.29	5.031	2.577	0.29	1
310.432	0.426	5.091	2.456	0.213	2
326.909	0.575	5.231	2.506	0.192	3
343.391	0.822	5.466	2.582	0.205	4
345.951	0.885	5.527	2.598	0.177	5
346.407	0.913	5.554	2.598	0.152	6
347.835	0.964	5.605	2.606	0.138	7
350.288	1.005	5.633	2.636	0.126	8
351.217	1.049	5.676	2.643	0.117	9
353.212	1.098	5.718	2.668	0.11	10
355.561	1.148	5.754	2.703	0.104	11
357.889	1.201	5.793	2.74	0.1	12
0.322	1.273	5.852	2.781	0.098	13
4	1.385	5.937	2.854	0.099	14
11.113	1.581	6.047	3.017	0.105	15
16.951	1.738	6.097	3.165	0.109	16
12.165	1.851	6.102	3.052	0.109	17
18.238	2.006	6.122	3.205	0.111	18
37.529	2.66	6.22	3.852	0.14	19
41.289	2.779	6.127	3.925	0.139	20
47.075	3.074	6.161	4.219	0.146	21
52.21	3.428	6.209	4.569	0.156	22
60.616	4.515	6.428	5.633	0.196	23
60.516	4.682	6.35	5.485	0.195	24
62.53	5.138	6.457	5.928	0.206	25
64.359	6.127	6.78	6.863	0.236	26
64.953	6.458	6.877	7.18	0.239	27
65.297	6.762	6.976	7.466	0.241	28
65.433	7.098	7.105	7.777	0.245	29
65.419	7.355	7.213	8.01	0.245	30
65.615	7.596	7.294	8.237	0.245	31
65.703	7.934	7.425	8.549	0.248	32
65.486	8.373	7.629	8.938	0.254	33
65.054	8.721	7.82	9.229	0.257	34
64.705	9.244	8.082	9.681	0.264	35
64.213	9.621	8.303	9.987	0.267	36
63.307	10.34	8.733	10.562	0.279	37
58.427	11.319	9.7	10.719	0.298	38
57.438	12.376	10.398	11.513	0.317	39
46.911	14.372	12.212	10.68	0.359	40
36.212	16.673	14.304	9.721	0.407	41
36.822	18.379	15.59	10.84	0.438	42
26.782	21.352	18.279	9.57	0.497	43



Table F5: Data for arm movements

time	position	velocity	acceleration
0	0	0	0
0.02	0	0	2
0.04	0	0	0
0.06	0	0	1.5
0.08	0	0	0
0.1	20	0.026	30
0.12	60	0.092	33.8
0.14	136	0.156	27.9
0.16	165	0.205	26
0.18	180	0.254	1.3
0.2	190	0.256	-28
0.22	180	0.22	-24
0.24	178	0.179	-24
0.26	176	0.147	0.4
0.28	175	0.092	4
0.3	178	0.03	-3.7
0.32	175	-0.001	0
0.34	175	-0.01	1.5
0.36	167	0.021	-1
0.38	175	0.02	1.2
0.4	175	0	0

## APPENDIX G





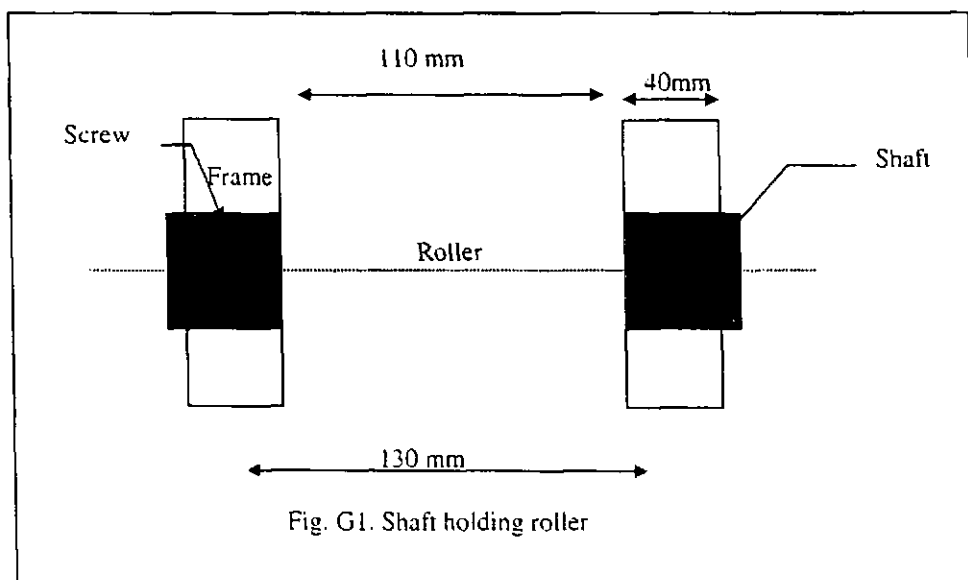
## Appendix G

### G1 Declaration

The material in this appendix is my original work. Contributions made by undergraduate students were under my supervision following my ideas and project concepts.

### G2 Structural Integrity of the Patternner Machine

Although the system is unlikely to fail due to the fact that the frame is too thick to bend compared to the weight exerted on it by the patient; calculations were made as an academic exercise to check the structural integrity of the system and the balance of the system. Note however that the only likely place where the system might fail is when parts are joined. Figure G1 shows an illustration of this fact. The roller or pulley mass is 6 kg held by a steel shaft supported by the frame. The shaft is mounted onto the frame via a steel bracket and by two 8 mm screws on each side. Depending on the way the screws are connected, there is either direct tensile stress or shear stress.



The direct tensile strength of the screws holding the shaft via a bracket was tested and yielded a strength of  $\sigma = 5.3 \text{ kN/mm}^2$  each, where the actual tensile strength of the machine  $\sigma_{\text{actual}} = 0.01276 \times 10^9 \text{ N/mm}^2$ . As shown in Figure G2 there are four centre supports connecting the two sides of the frame with a maximum bending moment of 398 Nmm and a maximum deflection of 0.0052 mm on each bar. The maximum weight that would be exerted on the frame is 20 kg, which will be evenly distributed on the belt, therefore the total maximum bending moment is 1.6 kN m and the maximum deflection is 0.02008 mm.

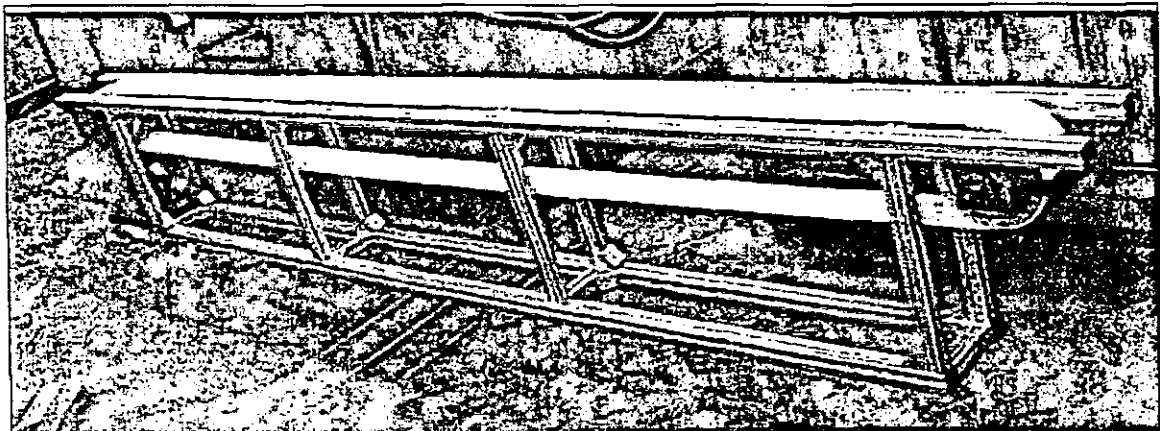


Fig. G2. Set-up of the Patterner Machine

Figure G3 shows the motor housing of the Patterner Machine. Note however, that the motor for the second unit will be placed on the opposite side of the unit adjacent to it. Originally the motor was to be mounted horizontally to the roller using a right-angled gear box. To achieve this, the system needs a custom-made roller and gearbox. For the purpose of this prototype the designer decided to mount the motor directly underneath the roller as shown in Figure G3 with the addition of two small pulleys connected via a small timing belt.

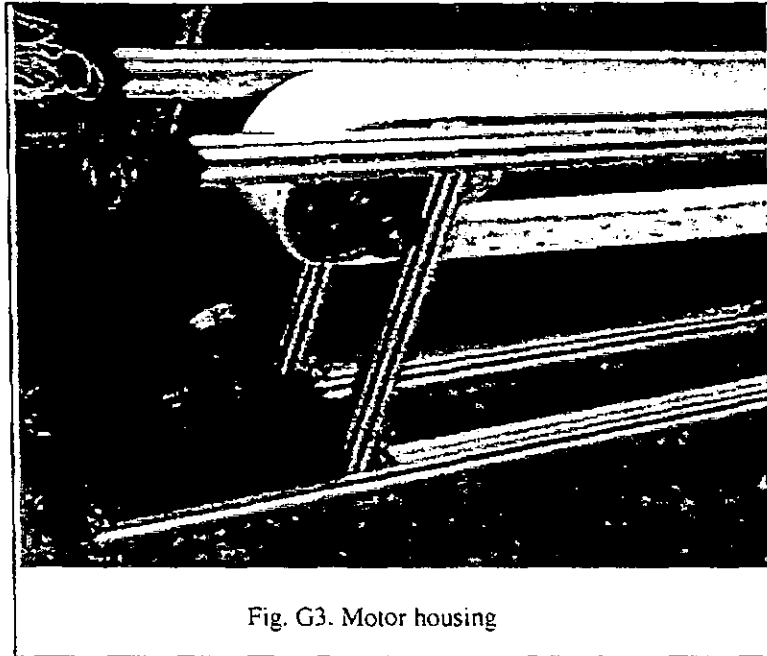


Fig. G3. Motor housing

The following tables list the electrical and mechanical parts used to construct the prototype, with their corresponding prices.

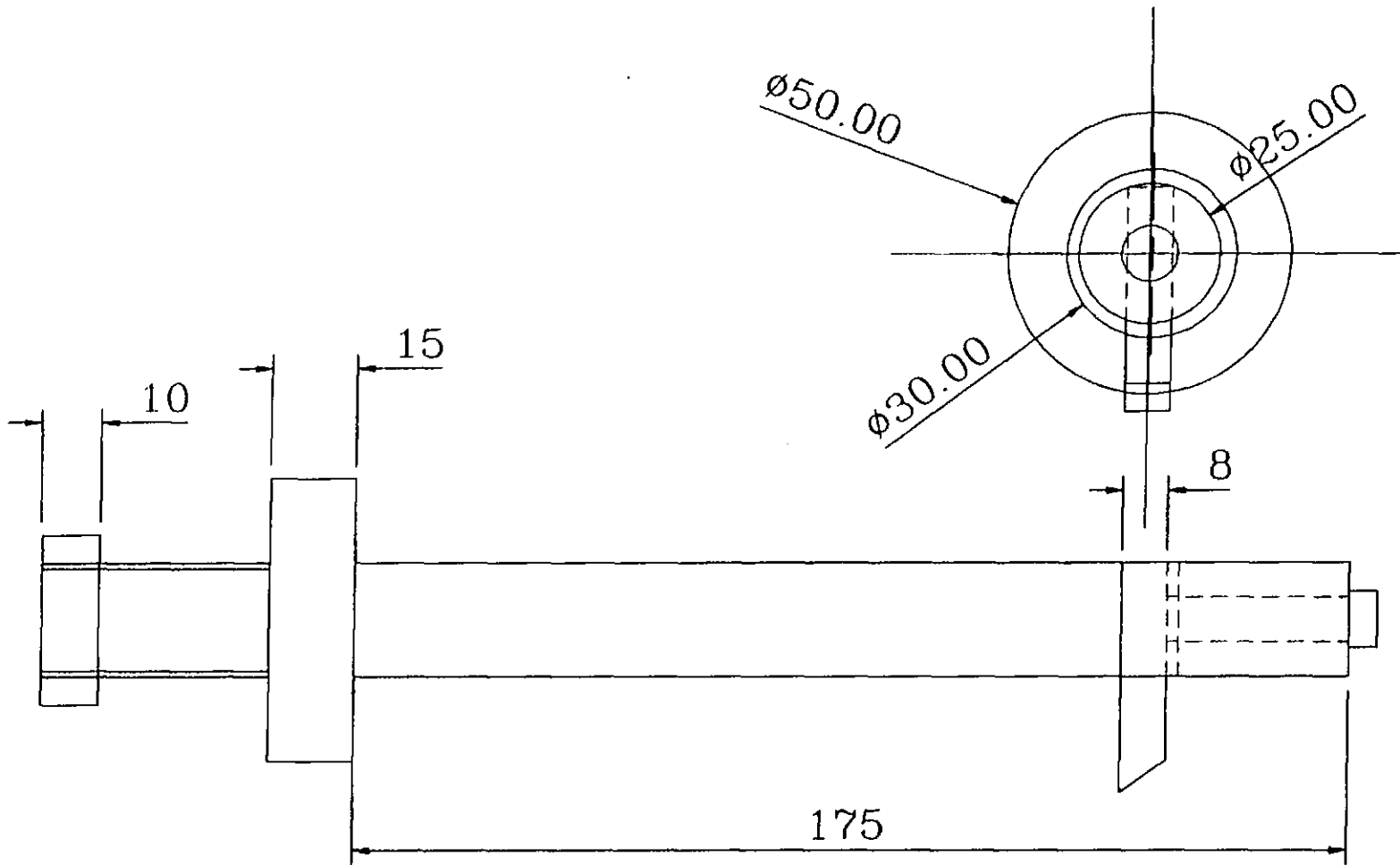
Table G1. Electrical parts of the system


Description	Quantity	Part No.	£/Unit	Total £
PC 386	1	N/A	250.00	250.00
Transformer 500 VA	1	58-0060	86.00	86.00
Feedback cable	1	44-0020-010	48.00	48.00
Motor+conn. +Enc+Gear	1	TBA	778.00	778.00
BRU 100	1	9103-0143	394.00	394.00
Euroservo	1	ES-M3	716.00	716.00
Backplane	1	ES-B4	93.00	93.00

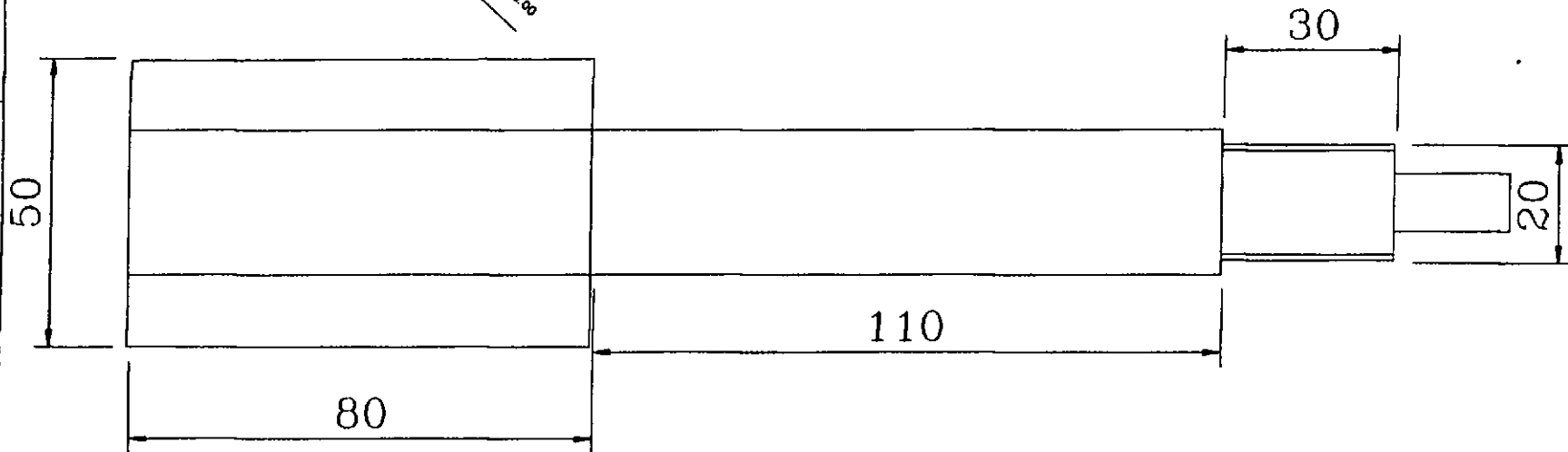
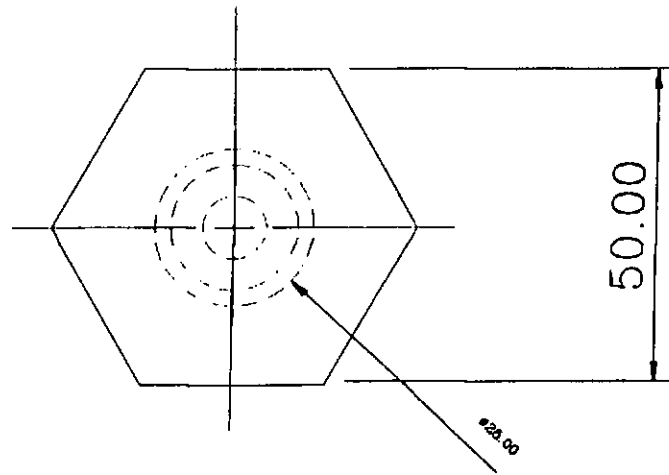
Table G2. Mechanical parts of the system

Description	Quantity	Size	Part No.	£/meter or £/unit	Total £
Profile 8, (40 x 40 -45°) triangle	1	2.50 m	0-0-373-45	15.09	37.72
Fasteners (T slot & nut)	137	M8	0-0-420-83	1.30	178.10
Square caps	8	40 x 40 mm	0-0-026-01	0.83	6.64
Fasteners standard	32	M8	0-0-026-07	1.18	37.76
Profile 8, (40 x 40) Square	17	1 m	0-0-026-03	17.50	318.41
Cover profile (32 x 4)	5	2 m	0-0-373-63	9.20	46
Rollers	2	190 □ x 110 mm	AL110ATK 10/60	90.31	180.62
Belt (main)	1	3 x 0.11 x 0.005	ATK 10	428.06	428.06
Belt	1	285 x 8 x 3	LO50	5.00	5.00
Small pulleys	2	30 x 60 mm	21 L 100	5.26	10.52
Bearings	4	95.3 x 95.3 x 38.84 mm	SF25	15.68	62.72
Shaft (mild steel)	2	25 □ x 210 mm	-	30	12.60





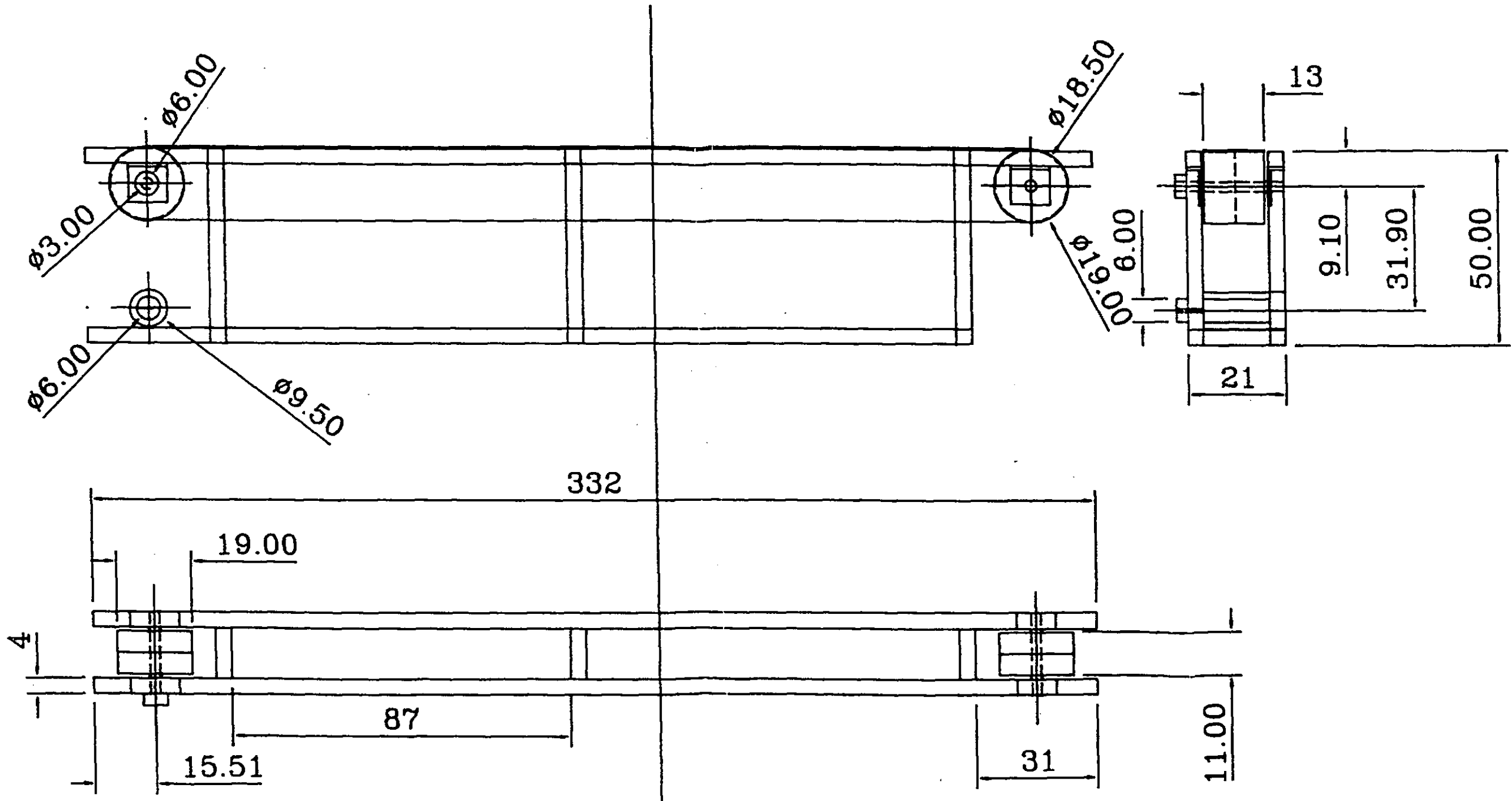
 <b>MIDDLESEX UNIVERSITY</b>	DRAWN BYR WILKINS	MATERIAL mild steel	PROJECTION	TITLE TOOL TO CUT KEY WAY IN ROLLER	DRG.NO.	REF.DRG.NO.	CHANGE
	COURSE ENG MECH II	TREATMENT MACHINED	TOLERANCE $\pm / - 2 \text{ mm}$				
	DATE 10/12/97	FINISH STANDARD	DIMENSIONS IN mm				
	Faculty of Technology School of Mechanical and Manufacturing Engineering		ORIGINAL SCALE 1 : 1				
							A4




DRAWN BY: H. J. WILKINS	MATERIAL: MILD STEEL
COURSE: BENG (MECH)	TREATMENT: MACHINED
DATE: 10/2/97	FINISH: STANDARD
Faculty of Technology School of Mechanical and Manufacturing Engineering	

PROJECTION	TITLE
TOLERANCE: +/- 0.025	HANDREEL
DIMENSIONS IN: mm	
ORIGINAL SCALE: 1:1	

DRG. NO.	ISSUE	DATE	CHANGE
REF. DRG. NO.			A4



 <b>MIDDLESEX UNIVERSITY</b>	<b>DRAWN BY</b> RICHARD W	<b>MATERIAL</b> ALUMINIUM	<b>PROJECTION</b>	<b>TITLE</b>  UNIT	<b>DRG. NO.</b>	<b>ISSUE</b>	<b>DATE</b>	<b>CHANGE</b>
	<b>COURSE</b> BENG MECH	<b>TREATMENT</b> EXTRUSION	<b>TOLERANCE</b> + / - 2 mm					
	<b>DATE</b> 18/2/97	<b>FINISH</b> STANDARD	<b>DIMENSIONS</b> IN mm					
	Faculty of Technology School of Mechanical and Manufacturing Engineering		<b>ORIGINAL SCALE</b> 1 : 10					
						<b>REF. DRG. NO.</b>		<b>A3</b>

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FRAME

ROLLER

FRAME

ROLLER SUPPORT BRACKET

TIMING PULLEY

BEARING

BEARING

SHAFT

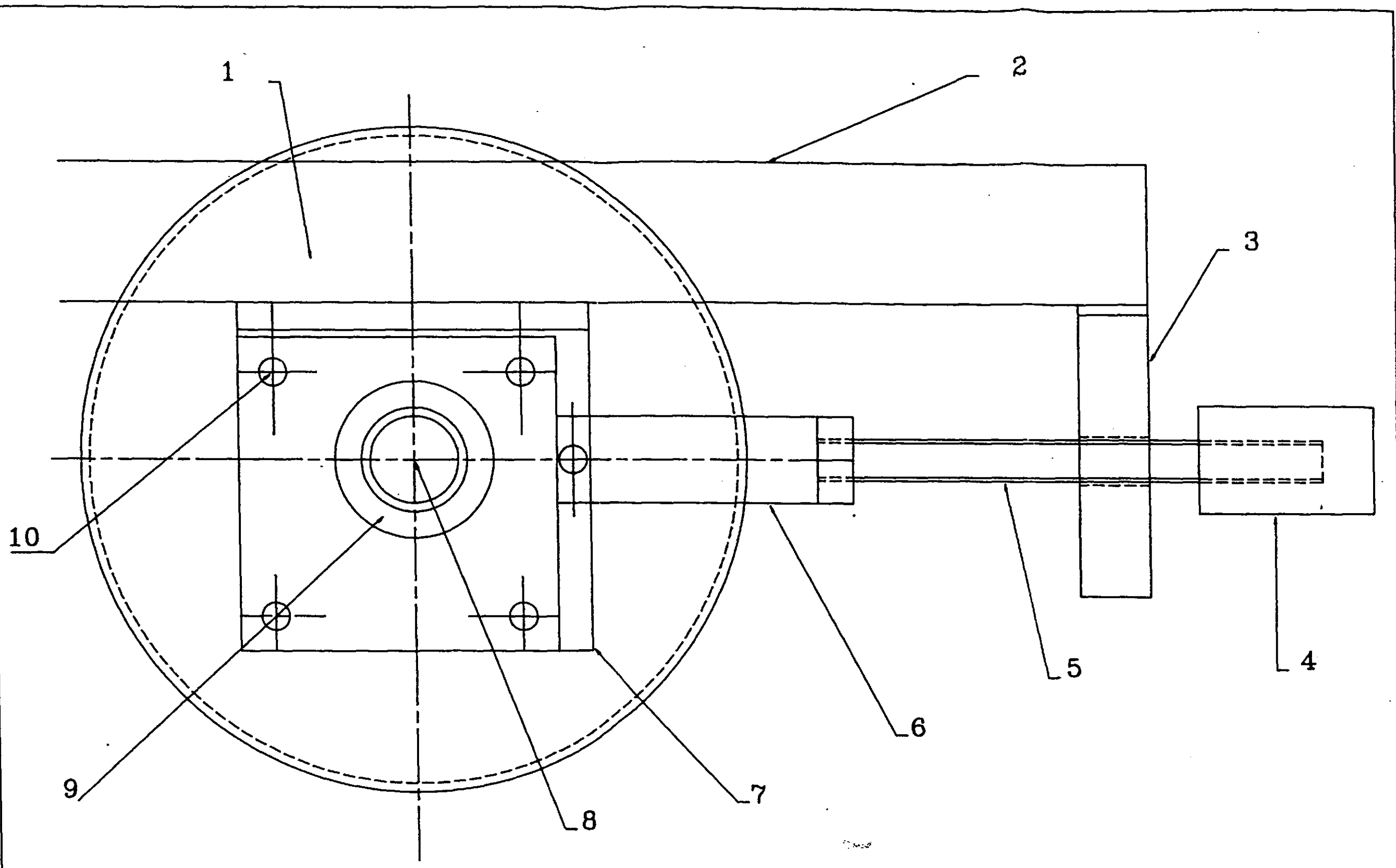



DRAWN BY R. WILKINS	MATERIAL ALUM AND M.S
COURSE BENG MECH	TREATMENT MACHINED
DATE 18/2/97	FINISH STANDARD
Faculty of Technology School of Mechanical and Manufacturing Engineering	

PROJECTION
TOLERANCE $\pm 2$ mm
DIMENSIONS IN mm
ORIGINAL SCALE 1 : 1

TITLE
ASSEMBLY DRAWING OF TRANSMISSION COMPONENTS

DRG.NO.	ISSUE	DATE	CHANGE
	REF.DRG.NO.		A3



 <p>MIDDLESEX UNIVERSITY</p>	DRAWN BY: WILKINS	MATERIAL: ALUMINIUM	PROJECTION	TITLE ASSEMBLY DRAWING OF ROLLER & TENSION DEVICE	DRG. NO.	ISSUE	DATE	CHANGE	
	COURSE: BENG MECH	TREATMENT: MACHINED	TOLERANCE: $\pm 2\text{mm}$			REF. DRG. NO.			
	DATE: 18/2/97	FINISH: STANDARD	DIMENSIONS IN: mm						
	Faculty of Technology School of Mechanical and Manufacturing Engineering		ORIGINAL SCALE: 1 : 1						A3

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## **APPENDIX H**

## **APPENDIX H**

### **UK PATENT APPLICATION**

Kavina, et.al, have produced a patent for the application of remedial treatment of brain injured patients. The following is the final version of the patent approved on 1/05/1996.



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(12) **UK Patent** (19) **GB** (11) **2 294 396** (13) **B**

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(54) Title of Invention

**Devices for restoring, enhancing or maintaining natural mobility**

(51) INT CL<sup>9</sup>; **A61H 1/02**

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(52) Domestic classification  
(Edition Q)  
**A5R REQ**

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DEVICES FOR RESTORING, ENHANCING OR MAINTAINING NATURAL MOBILITY.

Background :

Situations exist in which the live human or animal body has, through conditions especially such as brain injury, lost, potentially temporarily and in varying degrees, the ability to move and to be naturally mobile.

It is observed that many humans either born brain injured, or who have subsequently become brain injured through various causes after birth, cannot perform even basic movements such as creep and crawl, which are considered to be either important, or essential pre-requisite activities for the enablement of more advanced activities such as standing, walking and running.

Remedial treatment is at present, given manually to such brain injured patients, partly through specific input movements imparted to the patient by a team of helpers working together, as a group, in co-ordination, on various parts of the body of the patient.

It is considered that these input movements, manually imparted to the brain injured patient, contribute to a greater or lesser extent, in stimulating, training, patterning and programming the body of the brain injured patient, including the un-injured portions of the patient's partially injured brain.

The nature of these input movements, manually imparted, is designed to try to resemble, as far as is practicable in a manually imparted input method, the effects produced by natural movements such as creep and crawl.

It is noted, very significantly and importantly, however, that these input movements, manually imparted, are carried out as 'on the spot' input movements, with the patient lying in a prone position on a bench or table.

Hence, such manually imparted input movements are unable to closely resemble the actual sequences, experiences, and nature of natural movements such as creep and crawl.

Thus, during natural creep and crawl, when carried out in the forward direction, a subject's body is propelled forward, whereas, during the manually imparted input movements, there is no forward propulsion of the body of the patient.

Moreover, the postures adopted during natural creep and crawl are significantly different, from those adopted by a brain injured patient lying in a prone position during the execution of the manually imparted input movements.

Experience has shown that remedial input movement treatment, needs to be complemented by remedial output movement treatment, during which the patient attempts to perform, at first partially assisted by helpers, and subsequently unassisted, actual natural movements, termed output movements, such as creep, crawl, and

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other appropriate movements.

The manually executed remedial input movement treatment, in particular, is extremely labour intensive, requiring a team of three helpers for a brain injured patient of small size, and five helpers for a larger patient. Such helpers are required to be present daily at the home or residence or place of treatment of the patient, for many months, or even years, until the patient hopefully shows a marked improvement and a restoration of natural mobility.

It is difficult, and in many cases impossible, to arrange for such a large team of helpers on a regular basis, and this shortage of helpers may impede or even prevent the recovery of mobility of a brain injured patient. Moreover, even where a full team of helpers is available to a patient, members of the team who may have to leave the team, have to be replaced, possibly by relatively inexperienced new helpers who must develop their skills. Hence the quality and consistency of the input movement treatment can vary as a result of the composition of helpers in a team.

Moreover, helpers, being human, are subject to fatigue, and this limits the length of time over which the team of helpers can maintain their co-ordinated input movement treatment of the patient, before the team needs to rest and then continue. Hence, the level of stimulation that a brain injured patient receives, is limited by the fatigue experienced by the team of helpers.

In view of all the above factors, there are possibly significant advantages to be gained from devices, including mechanized, mechatronic, robotized and automated devices, that can be applied to the restoration, enhancement or maintenance of the natural mobility and motor functions of brain injured patients.

Previous patents and patent applications of four other inventors, have revealed considerable activity in attempting altogether four inventions, of powered devices for various input movements.

Two such inventions, namely, the Physio-Therapy Method and Apparatus, of Grant, J.L., United States Patent 3,824,993 , and the Physical Therapy Patterner, of Ross, J.A., Canadian Patent CA 1 163 883, are aimed to include specifically, the treatment of brain injured patients.

The other two inventions, namely, the Physical Therapy Patterner, of Sweeney, D.R., United States Patent 5,207,216, and the Bed for Motor Re-Education, of Patent Applicant OFMEC, and inventors. Pierangelo, M., Strada, P.E., Cavagnis, W., and Sanvito, A., European Patent Application EP 0 166 464 A2, also describe powered means of input movements to the body of patients, though not specifically or particularly or explicitly referring to brain injured patients.

However, none of the above four inventions, has included certain unique and significantly important features.

Thus, considering firstly, the remedial input movements,

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then, the Physio-Therapy Method and Apparatus, of Grant, as well as the Physical Therapy Pattern, of Ross, are both aimed at mechanizing the input movements, so that such mechanized input movements resemble as far as possible, the input movements as performed during the manually executed input movement treatment.

And, as has already been pointed out, such manually executed input movement treatment, and hence, the inventions of Grant and of Ross, are unable to provide input movements that would closely resemble the natural creep, crawl and other natural movements that normal children attempt to make during the development of natural mobility. The inventions of Grant and of Ross, are limited in their capability, to providing some form of mechanized 'on the spot' input movement, only.

Again, considering, secondly, the output movement treatment that is necessary as a very important complement to the input movement treatment, then, again, the inventions of Grant, and of Ross, have not been designed with the aim of facilitating the execution by the brain injured patient, of output movements that would closely resemble natural movements such as natural creep and natural crawl.

Indeed, it is evident that the invention of Ross does not even consider the provision of facilities for output movements as part of the invention.

The invention of Grant, does, in an oblique manner, consider the possibility of some effort being expended by the brain injured patient, or in other words, of some output movement by the patient, insofar as the invention of Grant includes a facility for freewheeling, which allows for the patient to expend some effort during the remedial movement therapy provided by the invention.

Hence, neither the inventions of Grant and of Ross, nor the inventions of Sweeney and of Pierangelo et al, make any provision to facilitate the execution by the brain injured patient, of output movements that would closely resemble the natural movements of creep, crawl and other natural output movements.

The present invention aims to offer a device that can be applied especially to the remedial treatment aimed at the restoration, maintenance and enhancement of natural mobility and motor function of brain injured patients. The objective of the present invention is to assist with remedial treatment that will especially allow such brain injured patients to ultimately regain natural mobility, so that ultimately these patients will possess their own natural mobility, without the aid of any devices to cause movements of their bodies.

In particular, the present invention aims to offer a device that will enable the execution of input movements into a brain injured patient, so that such input movements can closely resemble the natural movements of creep, crawl, and other movements, which normal humans learn during the various stages of the development

#### 4.

of natural, normal mobility. In this respect, the present invention is unique, and can thus, can be set apart from the four earlier inventions referred to above, since none of these four earlier inventions is capable of providing input movements that closely resemble natural movements such as natural creep, natural crawl, and other natural movements.

Furthermore, the present invention aims to offer a device that will also be able to facilitate the execution by a brain injured patient, of the very important output movements that must complement the input movements provided to the patient. Very significantly, the arrangement of the present device will make it possible for such output movements to be carried out in a manner that will allow the output movements to closely resemble natural movements, such as natural creep, natural crawl, and other natural movements.

Moreover, with the present invention, there will be a considerable reduction in the number of helpers needed, in comparison with the manual method of remedial treatment.

Thus, it is anticipated that the present invention will allow the execution of both the input movements and the output movements, with the aid of just one or at most two helpers. Such a helper or helpers will be needed to suitably connect the patient to the machine and disconnect the patient from the machine, and to operate the machine, as well as to provide the patient with some help that may possibly be needed particularly when the patient is attempting partially assisted output movements.

Furthermore, the present invention will remove or reduce various limitations and difficulties that can exist when the treatment to brain injured patients is applied purely manually.

#### **Description:**

A remedial device for restoring, enhancing or maintaining the motor functions and natural mobility of a brain injured patient, and comprising a plurality of independently driven and programmable endless belts arranged side by side, such that the patient's arms, legs, etc., may rest thereon for controlled movement, means for attaching or connecting the patient's arms, legs, etc., to the belts, and at least one harness suspended overhead for supporting the patient's head and torso, such harness having the possibility of being provided with powered movement for the head in suitable synchronism with other input movements provided by the belts to various other parts of the body, and furthermore, such a present remedial device being clearly distinguishable from other previous devices, such as the Physical Therapy Patterner, of Ross, J.A., Canadian Patent

CA 1 163 883, ( Filed, March 10, 1981, Issued, March 20, 1984 ),

as well as the Physio-Therapy Method and Apparatus, of Grant, J.L., United States Patent 3,824,993, ( Filed January 2, 1973, Issued July 23, 1974 ), and the Bed for Motor Re-Education, of patent applicant OFMEC, and inventors, Pierangelo, M., Strada, P.E., Cavnagnis, W., and Sanvito, A., European Patent Application EP 0 166 464 A2, ( Filed, February 11, 1985, Issued, January 2, 1986 ), and the Physical Therapy Machine, of Sweeny, D.R.,

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United States Patent 5,207,216, ( Filed, October 5, 1992, Issued, May 4, 1993), in that the present remedial device, by virtue of its unique constructional features, namely, in particular, the unique endless belts, that are moreover, independently programmable, together with the accompanying harness or harnesses, and the means of attaching or connecting the patient's arms, legs, etc., to these belts, is capable of providing input movements that closely resemble actual, natural, creep, crawl, walking, and other natural movements, so that for instance, during forward creep, crawl, walking, and other forward input movements, the patient not only experiences movements of arms, legs, head, etc., but also forward propulsion, whereas previous devices of other inventors, as referred to, above, can only provide 'on the spot' movements which do not closely resemble natural input movements such as natural creep, crawl, walking, etc., and which do not include natural, forward propulsion of the patient, and, moreover, such a present remedial device also differing from the above previous remedial devices, in that, with the present device, by virtue of its constructional features, in particular, the endless belts, that are independently programmable, together with at least one harness, and also, with an overhead rail arrangement, from which the harness may be suspended, as well as translated along the rail or rails, the patient is additionally and uniquely, capable of executing output movements, either partially assisted, or unassisted, in a manner closely resembling natural movements, such as natural creep, crawl, walking, and other natural movements.

### **Essential Technical Features:**

In particular, the present device incorporates the following essential technical features:-

- (1) A device contains several programmable, endless, conveyor belts,- ( endless in much the same way that a car fan-belt or a bicycle chain or a conveyor belt as found in a supermarket checkout, is endless ), positioned side by side, namely, adjacent to one another, and provided with the facility to be driven independently of one another, but in a certain required manner relative to one another.
- (2) Each belt is mounted over its own separate driver roller and also over its own separate idler, tensioner roller, or set of idler, tensioner rollers, much in the manner of a conveyor belt,- ( such as a conveyor belt found in a supermarket checkout ), and thus a device contains several such independent conveyor belts, positioned side by side, namely, adjacent to one another, and supported and packaged within a suitable housing and structure.
- (3) A patient's hands and lower legs,- ( for crawl inputs ), or torso, arms and legs,- ( for creep inputs ), or other parts of the body, such as the feet, - ( for inputs such as walking, in order to make the device increasingly versatile, for the execution of inputs additional to creep and crawl ), are allowed to rest on these belts , or are suitably connected to these

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belts.

(4) Both input and output movements are classified into homolateral movements and cross movements. Ofcourse, in general, movements can be either forward movements or backwards movements, and thus, for instance, it is possible to crawl and walk in either a forward or backward direction. However, unless otherwise stated, the movements are assumed to be forward movements. For homolateral movements, the right arm and right leg are involved, together, in forward movements, and then the left arm and left leg are involved, together, in forward movements, and so on in repeated cycles. A similar argument applies to backwards movements as it did to forward movements, except that the word backwards is used instead of the word forwards.

(5) For cross movements, the right arm and left leg are involved, together, in forward movements, and then the left arm and right leg are involved, together, in forward movements, and so on in repeated cycles.

(6) For homolateral creep inputs, using a device with four belts, the patient faces the belts, in a horizontal posture. The patient's torso is connected to the two inner, i.e., central belts, which are now arranged to move in unison and thus effectively to work together as one broader belt. The patient's left arm and left leg are connected to the left side outer belt, and the patient's right arm and right leg are connected to the right side outer belt. Thus, a forward movement of the left side outer belt, produces a forward movement of the left arm and left leg together, whereas a forward movement of the right side outer belt produces a forward movement of the right arm and right leg together. A forward movement of the two inner, i.e., central belts, in unison, produces a forward movement of the torso.

(7) For cross creep inputs, using a device with six belts, the patient faces the belts, in a horizontal posture. The patient's torso is connected to the two innermost, i.e., most central belts, which are now arranged to move in unison and thus effectively to work together as one broader belt. The patient's left arm is connected to the left side outermost belt, the right arm to the right side outermost belt, the left leg to the left side intermediate belt and the right leg to the right side intermediate belt. Such an arrangement provides for independent control of the movements of the torso, left arm, left leg, right arm and right leg. Thus, a simultaneous forward movement of the left side outermost belt and the right side intermediate belt, produces a simultaneous forward movement of the left arm and right leg. A simultaneous forward movement of the right side outermost belt and the left side intermediate belt, produces a simultaneous forward movement of the right arm and left leg. A forward movement of the two innermost, i.e., most central belts, in unison, produces a forward movement of the torso.

(8) Such a device, with six belts is also be suitable for homolateral creep inputs. In this case, a simultaneous forward movement of the left side outermost belt and the left side intermediate belt, produces a simultaneous forward movement of

## 7.

the left arm and left leg. A simultaneous forward movement of the right side outermost belt and the right side intermediate belt,

produces a simultaneous forward movement of the right arm and right leg. A forward movement of the two innermost belts, in unison, produces a forward movement of the torso.

(9) For crawl inputs, using a device with four belts, the patient faces the belts in a hands and knees or piggy-back posture. The patient's left hand is connected to the left side inner belt, the right hand to the right side inner belt, the left leg to the left side outer belt and the right leg to the right side outer belt. Crawl is usually assumed to be classified as a cross movement, but a device with four belts is also suitable for homolateral crawl.

(10) Both homolateral and cross crawl inputs, can also be produced by a device with six belts, the requirement for these inputs being the use of four effective belts.

(11) Thus, in general, all the above creep and crawl input movements, namely, homolateral and cross creep, as well as homolateral and cross crawl, can be provided to a brain injured patient by a device with an arrangement of six belts. If only homolateral creep, and homolateral and cross crawl inputs are considered, a device with an arrangement of four belts appears to be adequate. Ofcourse, it is quite possible to consider devices with more than six belts, that would be able to provide all these creep and crawl input movements.

(12) The arrangement of belts is likened to a multi-belt conveyor. As such, this multi-belt arrangement has two extremities or extreme positions for conveyance of the patient, namely, an extreme starting position and an extreme finishing position. Depending upon the size of a patient, such a multi-belt arrangement having a certain distance between its extremities, also has a total or maximum working length, representing a maximum distance over which a given patient can be conveyed, between the extreme starting and extreme finishing positions. Ofcourse, the patient does not necessarily have to be conveyed between the extreme starting and extreme finishing positions, but may be placed to start at any intermediate position and to finish being conveyed at any desired position before the extreme finishing position.

(13) In order to achieve the desired forward, input movements that must be imparted to the patient, the belts are all individually programmable for stepped or any other form of motion, including continuous motion, in a forward direction, and for rest. The belts are also individually programmable for any required motion in a reverse direction, in order to reposition the patient at a starting position after the patient has reached the end of a working length. The patient is then again subjected to a series of stepped forward input motions until the patient has again reached the end of a working length, and then again moved in a reverse direction, in order to be repositioned at the starting position, and so on, in repeated cycles.

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(14) Just for the record, and for the sake of completeness, it needs to be mentioned that although a unique feature and a unique advantage, of the present device, is its capability of providing input movements that closely resemble natural movements, the present device is, additionally, also capable of providing 'on the spot' movements, such as, 'creeping on the spot', 'crawling on the spot', 'walking on the spot'. For such 'on the spot' input movements, there is no transportation of the patient as a whole from one location to a further, distant location, as an integral part of the input movements.

During such 'on the spot' input movements, the reverse motions provided by the belts complement the forward motions, so that both forward and reverse motions are considered as parts of the remedial treatment input movements provided to the patient. All belts are programmable for any required forward as well as reverse movements.

Any such 'on the spot' input movements, cannot closely resemble natural input movements, such as natural creep, crawl, and walking, since, during natural movements, there is not only movement of the limbs and other parts of the body, but also transportation of the body as a whole, whereas, during 'on the spot' creep, crawl, and walking input movements, there is no such transportation of the body as a whole.

A unique feature of the present device is, that by virtue of its constructional and operational features, the device is, indeed, capable of providing input movements to the patient, that closely resemble natural input movements, including transportation of the body as a whole as an integral part of the input movements.

(15) Also, just for the record, and for the sake of completeness, it is noted here that devices that are required to provide only 'on the spot' input movements, can be much shorter than devices capable of providing both 'on the spot' input movements as well as input movements closely resembling natural movements. 'On the spot' input movements do not involve actual transport of the patient as a whole from one location to a further, distant location, and this is why devices providing only 'on the spot' input movements can be much shorter than devices capable of providing input movements closely resembling natural movements. However, as stated earlier, the devices that are of main interest, to us, are those capable of providing input movements that closely resemble natural movements, although such devices can also, additionally, provide 'on the spot' input movements.

(16) All devices are provided with harnesses that suitably support a patient's head and torso. The harnesses are suspended from, and connected to, a central overhead rail or central overhead rails, positioned above and parallel to the belts, the rail or rails being an integral part of the structure of the complete devices. A system of rollers or wheels, running on the rail system, supports the harnesses, so that when the patient is placed into the harnesses, and suspended by the harnesses, the weight of the patient is supported through the harnesses. As the patient is moved in either a forward or reverse direction by the



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belts, the harnesses move with the patient because of the connection of the harnesses to the system of rollers or wheels running on the overhead rail system.

(17) Provision is made for adjusting the height position of the harnesses with respect to the belts and the rail system, so that the patient's torso can be suspended as required, in an appropriate and comfortable position whilst the patient is being provided with the input movement treatment by the belts. Such support of the weight of the patient by the harnesses, is required, for instance, during crawl input movements.

(18) The design of the harnesses also allows for the deliberate provision of powered or energized cyclic, clockwise and counterclockwise rotation of the patient's head, through suitable, small angles, the rotation of the head being synchronized with the input movements provided to the patient by the belts. This cyclic head rotation is considered to be an essential component of the total input movement, during creep and crawl inputs for instance.

(19) The detailed construction of the belts, and the detailed arrangements for stepped or other motions of the belts, take into account that belts must not slip, because such belt slip causes errors in belt positions. Thus, special types of flat belts, - ( sometimes described as timing belts ), are appropriate, since these types of belts can engage with toothed rollers,- ( a familiar example of engagement being that between a bicycle chain and its associated toothed sprocket wheels ). Thus, each belt, of an endless construction,- ( in the same way that a conveyor belt, or a car fan belt, or a bicycle chain, is endless ), operates between its own independent set of two toothed rollers, one a driving roller and the other an idler roller. Means are provided for maintaining sufficient tension in each belt.

(20) All belts are provided with means for attaching or connecting a patient to the belts in a suitable manner. Thus, belts are provided with attachment or connecting devices such as loops, and straps, suitable for attaching or connecting a patient's hands, arms, legs and feet to the belts. The loops or straps, as well as the junctions between the belts and the loops or straps, are sufficiently flexible and with sufficient capability of pivoting or rotating at the junctions, in order to provide movement of the loops and straps as required for adequate freedom, comfort and safety of the patient, during the input movement treatment imparted to the patient by the belts.

(21) Each belt is capable of being individually and independently programmed, for control of its movement. Atleast three different techniques of programming are possible to use, all techniques being based on already well known techniques used for the programmable control of robots. One or more of these techniques is incorporated in devices for the remedial treatment of brain injured patients. The three techniques are as follows:-

(i) Keyboard programming, during which the detailed steps of forward and reverse movements, and the stationary or rest

## 10.

positions and periods of each belt, can be individually called up from a keyboard. Forward and reverse movements of a belt are called up with respect to distance of movement, as well as acceleration, deceleration and velocity profiles.

(ii) Lead-through teach programming, during which each belt is individually power driven, or in other words led through all the detailed steps of forward and reverse movements, as well as the stationary or rest positions. All the steps are stored in the memory of the device during this lead-through teach programming exercise, whilst the device is in the teach mode. The durations of rest periods, as well as acceleration, deceleration and velocity profiles, are all also stored in the memory of the device, during lead-through teach programming. The individual steps for each belt can then be reproduced at the belt by putting the device into the playback or run mode.

(iii) Walk-through teach programming, during which each belt is suitably temporarily disengaged, if required, from its power drive arrangement and manually walked through, or in other words manually moved through, the different steps to be taught, which are stored in the memory of the device. The disengagement would be required when it is not otherwise possible to move the belt manually. The durations of rest periods, as well as acceleration, deceleration and velocity profiles, are all also stored in the memory of the device, during walk-through teach programming. After completion of the walk-through teach programming, all belts are suitably re-engaged with their power drive arrangements, if it had been required to previously disengage them. The individual steps for each belt can then be reproduced at the belt by putting the device into the playback or run mode.

(22) When applying these devices for the remedial output movement treatment of brain injured patients, the devices are used in one of the following ways:-

(i) With the devices switched off, the belts are used just as a platform over which the patient moves, to perform outputs, assisted if required, manually, by one or at most two helpers. The arrangement of harnesses already present on the devices, is used, if required, to support the patient during output movement treatment.

(ii) The devices are selectively power driven during output movement treatment, to provide just sufficient powered assistance to the patient, to complement the patient's own efforts. For one of the methods used to achieve this, the overhead rail system is designed using rails in the form of racks, and the rollers or wheels running on the rail system are designed as pinions engaging with the rack type rails. During output movement treatment, the rollers or wheels are suitably power driven, to provide just sufficient assistance to the patient, to complement the patient's own efforts. The patient is, in this case, supported by harnesses that are connected to the system of rollers or wheels.

(iii) Unpowered assistance to the patient during output movement

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treatment is provided by arranging the roller or wheel system to be attached to one end of a cable or chain that runs respectively over a pulley or sprocket. The other end of the cable or chain is provided with a mass carrier onto which a set of masses can be mounted. Thus, just sufficient mass can be mounted on the carrier to provide the required assistance to the patient during output movement treatment. The portion of cable or chain between the roller system and the pulley or sprocket, is horizontal. The portion of cable or chain between the pulley or sprocket and the mass carrier, is vertical. The mass supplies the driving force derived from acceleration due to gravity, as a result of Newton's Second Law, which states that force equals mass multiplied by acceleration. The value of the mass placed on the carrier is chosen so as to provide just sufficient force to the system of rollers or wheels, to complement the patient's own efforts during output movement treatment. The patient is, in this case, supported by harnesses that are connected to the system of rollers or wheels.

(23) The devices are capable of being used for both input and output remedial movement treatment, not only for creep and crawl, but also for various other classes of movement including walking. The devices can be used for normal, forward direction movements, and also for 'on the spot' movements. If required, the devices can also be used for movements in a backwards direction.

(24) All devices for the remedial input and output movement treatment of brain injured patients are provided with various comprehensive safety features, to protect the patient as well as the operator and helpers. Thus, the patient is protected from excessive forces, torques, and dangerous movements and postures, through the incorporation in the devices, of mechanical overload protection facilities, such as slip clutches, and force, position and torque sensing and limiting arrangements, which may stop the whole device, for safety. Protection is provided to avoid entrapment of limbs and clothing in the devices, that could result in accidents and injuries, and to avoid accidents or injuries from the electrical energy used in the devices.

(25) Devices described earlier, are designed for the needs of patients of various sizes. This is done as follows:-

(i) Provision is made for a complete range of sizes of devices, to suit patients that are of large, medium and small size. Thus, the range of sizes includes models of devices that are large, medium and small.

(ii) Within any particular model of device within the size range, say for example, a device of small size, provision is made for any necessary adjustment to the device, to cater for small patients of various sizes between the upper and lower limits of the small size. Such adjustment is effected by using a design of modular construction, which also has features that facilitate the adjustment process. Such modular construction is also used as necessary in order to construct devices to cover the different models within the complete size range, from a rationalized set of elements and modules of construction. This approach of

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construction is economically attractive in that the number of different components within the inventory of elements and modules required for construction can be kept to a minimum.

(26) The design of devices for remedial input and output movement treatment of brain injured patients employs the use of actuators, control systems and sensing systems that are commonly used in robotic and mechatronic systems. Such actuators, control systems and sensing systems for the devices can include the following:-

(i) Electric motors of various types, such as continuous rotation a.c. motors, d.c. motors of both the continuous rotation and stepper variety, and linear motors.

(ii) Electrical solenoids.

(iii) Pneumatic and hydraulic actuators, including motors and cylinders.

(iv) Various commonly applied techniques and components for the control of actuators, including techniques such as open loop and feedback control, pulse width modulation control, and control by the use of neural networks, and components such as optical encoders, switches, and pneumatic and hydraulic control valves.

(v) Systems for both 'internal' and 'external' sensing. In this context 'internal' sensing provides a comparison, for position control purposes of the device, between an actual position and the final, desired, programmed or targetted position, and 'external' sensing provides information to the device, of various factors external to the device, in order to allow the device to react suitably to such external factors.

(27) In order to allow devices for the remedial input and output movement treatment of brain injured patients, to be used not only for creep and crawl movement treatment, but also for movements

such as walking, and postures such as standing, powered and/or unpowered components are attached as necessary to the basic frame of the devices, for such special needs, and can be taken off when not required. Such 'add on', 'take off' components include a ladder placed horizontally overhead, above the patient, so that the patient can grip the rungs of the ladder during movements such as walking with arms raised and postures such as standing with arms raised. Additional harnesses that are suitable for the support of a patient during movements such as walking, and postures such as standing, are also provided.

(28) With respect to the synchronized, powered, clockwise and counterclockwise rotation of the patient's head through small angles, required to be provided by a region of the harness that also supports the patient's head, such rotation is effected through the use of actuators, such as electric motors, or electric solenoids, that provide the necessary movement to a particular region of the harness that supports the patient's head.

Such actuators are controlled so that the clockwise and

counterclockwise rotations of the patient's head, through small angles, are synchronized as required, with the movements provided to other parts of the patient's body by belts or manipulators existing in a device.

### Historical Background:

In the past, the consequences of brain injury, including those accompanying the condition often termed Cerebral Palsy, - ( Cerebral = to do with the brain; Palsy = paralysis, trembling, convulsions ), were considered to be untreatable. With the passage of time, treatments have been and are being developed, which may vary from organization to organization.

In Hungary, the organization now called the Andras Peto Institute for Motor Disorders, - ( address, Kutvolgyi ut 6, Budapest XII, Hungary H-1125 ), was founded by Dr. Andras Peto in 1952. In 1968, a state decree made physicians throughout Hungary responsible for the registration of all children with motor disorders, - ( disorders resulting in problems with movement and mobility, because of damage to areas of the brain ), at the Peto Institute. Details of the Peto programmes are summarized in a Conductive Education Fact Sheet available from Scope, (previously called The Spastics Society) , 12 Park Crescent, London W1N 4EQ, phone 0171 636 5020, fax 0171 436 2601. The Peto programme has now spread to institutes in the United Kingdom, including Birmingham.

In the United Kingdom, the British Institute for Brain Injured Children, - ( address, Knowle Hall, Knowle, Bridgwater, Somerset, TA7 8PJ, phone 01278 684060, fax 01278 685573 ), was founded in 1972, by Mr. I.K. Pennock, after his first child unfortunately became brain injured through the side effects of the whooping cough vaccine, - ( see page 18 of the book ' Rescuing Brain

Injured Children ', by Keith Pennock, 1991, ISBN 1-85398-030-7). The work of the British Institute for Brain Injured Children has been included in a Therapy Information Sheet, Doman-Delacato

Therapy, available from Scope, (previously called the Spastics Society). The British Institute for Brain Injured Children uses the Doman-Delacato therapy technique, developed by Glenn Doman and Carl Delacato, who were influenced by the work of Dr. Temple Fay, a neurosurgeon. Doman and Delacato had been dissatisfied

with the results of previous methods of therapy, and had begun to focus on the treatment of the injured brain itself. In 1962, Dr. Glenn Doman founded The Institute for the Achievement of Human Potential, in Philadelphia, Pennsylvania, United States of America, to promote therapy based on such treatment. Such therapy offers a brain injured patient, learning or re-learning experiences which are considered to stimulate dominant, un-injured areas of the brain and encourage such areas to take over the functions of those areas that have been damaged, - ( see the book. ' What to do about your Brain Injured Child ', by Dr. Glenn Doman, 1973, ISBN 0-224-00934-6 ).

The methods of imparting remedial treatment to brain injured patients, as practised by organizations and centres of expertise such as the above mentioned, are largely manual methods, using

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for the most part, simple aids as appropriate, to assist with the manual methods of treatment.

As discussed earlier, under the heading, Background, very important aspects or elements of such manual methods of treatment used presently, are extremely labour intensive, and the treatment imparted using these aspects or elements, needs to be carried out during a period of several hours per day, in many cases for several months, or even years, until a marked improvement in the condition of the patient is detected. It is often difficult or impossible to arrange for the labour, or in other words, the helpers needed for such labour intensive aspects or elements of the treatment. The helpers, themselves, have limitations imposed by fatigue, and by the time needed to learn these manually imparted aspects or elements of the treatment.

The purpose of the present invention is to provide devices, including mechanized, mechatronic, robotized and automated devices, as described earlier, under the heading, Background, that enable a very significant reduction in the amount of labour needed for the remedial treatment of brain injured patients. Such devices, moreover, do not have limitations such as fatigue, and significant variations in the quality and consistency of treatment, that can be experienced by human helpers.

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**Claims:**

(1) A remedial device for restoring, enhancing or maintaining the motor functions and natural mobility of a brain injured patient, and comprising a plurality of independently driven and programmable endless belts arranged side by side, such that the patient's arms, legs, etc., may rest thereon for controlled movement, means for attaching or connecting the patient's arms, legs, etc., to the belts, and at least one harness suspended overhead for supporting the patient's head and torso, such harness having the possibility of being provided with powered movement for the head in suitable synchronism with other input movements provided by the belts to various other parts of the body.

(2) Devices as claimed in Claim 1, wherein each belt is mounted over its own separate idler, tensioner roller, or set of idler, tensioner rollers, much in the manner of a conveyor belt,- ( such as a conveyor belt found in a supermarket checkout ), so that a

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device contains several such independent conveyor belts, positioned side by side, namely, adjacent to one another, and supported and packaged within a suitable housing and structure.

(3) Devices as claimed in Claim 1 and/or Claim 2, wherein for the remedial input movements, provided by the remedial device to the brain injured patient, the arrangements of the endless belts, as well as the programming of the endless belts, would need to be classified as providing either homolateral movements or cross movements, such input movements provided by the device including forward movements or backwards movements to the patient, so that, when considering forward movements, then, for movements classified as homolateral, the input movements provided by the device must be such that the right arm and right leg are involved, together, in forward movements, and then the left arm and left leg are involved, together, in forward movements, and so on in repeated cycles, and furthermore, when considering forward movements, then, for movements classified as cross, the input movements provided by the device must be such that the right arm and left leg are involved, together, in forward movements, and then the left arm and right leg are involved, together, in forward movements, and so on in repeated cycles, and, moreover, a similar argument applies to the arrangement and programming of the device for any backwards input movements that the device may be called upon to provide, as applied for the forwards movements, except that the word backwards is used instead of the word forwards.

(4) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3, wherein for homolateral creep inputs, using a device with four belts, the arrangement and programming of the device must be such that the patient faces the belts, in a horizontal posture, with the patient's torso is connected to the two inner, i.e., central belts, which are now arranged to move in unison and thus effectively to work together as one broader belt, and with the patient's left arm and left leg being connected to the left side outer belt, and the patient's right arm and right leg being connected to the right side outer belt, so that, a forward movement of the left side outer belt, produces a forward movement of the left arm and left leg together, whereas a forward movement of the right side outer belt produces a forward movement of the right arm and right leg together, and a forward movement of the two inner, i.e., central belts in unison, produces a forward movement of the torso.

(5) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3, wherein for cross creep inputs, using a device with six belts, the arrangement and programming of the device must be such that the patient faces the belts, in a horizontal posture, with the patient's torso connected to the two innermost, i.e. most central belts, which are now arranged to move in unison and thus effectively to work together as one broader belt, and with the patient's left arm connected to the left side outermost belt, the right arm to the right side outermost belt, the left leg to the left leg intermediate belt and the right leg to the right side intermediate belt. such an arrangement and programming of the device providing for independent control of the movements of the



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torso, left arm, left leg, right arm and right leg, in the manner that a simultaneous forward movement of the left side outermost

belt and the right side intermediate belt, produces a simultaneous forward movement of the left arm and right leg, and moreover, a simultaneous forward movement of the right side outermost belt and the left side intermediate belt, produces a simultaneous forward movement of the right arm and left leg, and, furthermore, a forward movement of the two innermost, i.e. most central belts, in unison, produces a forward movement of the torso.

(6) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3, wherein a device with six belts is also suitable for homolateral creep inputs, in which case, the arrangement and programming of the device must be such that a simultaneous forward movement of the left side outermost belt and the left side intermediate belt, produces a simultaneous forward movement of the left arm and left leg, and moreover, a simultaneous forward movement of the right side outermost belt and the right side intermediate belt, produces a simultaneous forward movement of the right arm and right leg, and furthermore, a forward movement of the two innermost belts, in unison, produces a forward movement of the torso.

(7) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4, wherein a device with four belts is also suitable for both homolateral and cross crawl inputs, although crawl is usually assumed to be classified as a cross movement, so that for crawl inputs, the patient's left hand is connected to the left side inner belt, the right hand to the right side inner belt, the left leg to the left side outer belt and the right leg to the right side outer belt.

(8) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 5, wherein a device with six belts is also suitable for both homolateral and cross crawl inputs, so that, in one particular arrangement of the device, there are only for four effective belts, only four individual belts out of the six individual, available belts, being used, as effective belts, and, furthermore, alternatively, in a different arrangement if required, four of the six individual belts are used as two effective belts, by arranging that these four individual belts are programmed so that two of these belts operate together as one combined effective belt, and the other two of these belts operate together as another different combined effective belt, and that the remaining two individual belts out of the six individual belts, are used as two separate, further, effective belts.

(9) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6, and/or Claim 7 and/or Claim 8, wherein all homolateral and cross creep and crawl inputs can be provided, using devices with a minimum of six individual belts, and moreover, all homolateral and cross creep and crawl inputs can also be provided, using devices with more than six individual belts, such that some or all of the total number of individual belts are used, either as separate, individual, effective belts only, or as separate individual

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effective belts together with combined effective belts, or as combined effective belts only.

(10) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9, in which the arrangement of belts is likened to a multi-belt conveyor, such that, this multi-belt arrangement has two extremities or extreme positions for conveyance of the patient, namely, an extreme starting position and an extreme finishing position, and moreover, depending upon the size of a patient, such a multi-belt arrangement has a certain distance between its extremities, and also has a total or maximum working length, representing a maximum distance over which a given patient can be conveyed, between the extreme starting and extreme finishing positions, and furthermore, the patient does not necessarily have to be conveyed between the extreme starting and extreme finishing positions. but may be placed to start at any intermediate position and to finish being conveyed at any desired position before the extreme finishing position.

(11) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10, in which the belts are all individually programmable for all required forms of motion, both stepped and continuous, in either a forward or backward direction, and also for rest, as necessary, to impart the remedial input movement treatment as well as to allow the remedial output movement treatment, such that, in some instances, the backward or reverse motions of the belts complement the forward motions of the belts, so that both forward and reverse motions provided by the belts are parts of the remedial movement treatment of the patient, whereas, in other instances, for example, when considering the remedial input movement treatment in the forward direction, then, the backward or reverse motions of the belts have the purpose of repositioning a patient at a starting position after the patient has experienced an appropriate, partial or complete working length of remedial input movement treatment in the forward direction.

(12) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11, in which harnesses are provided that suitably support a patient's head and torso, the harnesses being suspended from, and connected to, a central overhead rail or central overhead rails, positioned above and parallel to the belts, the rail or rails being an integral part of the structure of the complete devices, such that a system of rollers or wheels, running on the rail system,

supports the harnesses, so that when the patient is placed into the harnesses, and suspended by the harnesses, the weight of the patient is supported through the harnesses, and, moreover, as the patient is moved in either a forward or reverse direction, by the belts, the harnesses move with the patient because of the connection of the harnesses to the system of rollers or wheels running on the overhead rail system, and furthermore, so that provision is made for adjusting the height position of the

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harnesses with respect to the belts and the rail system, so that the patient's torso can be suspended as required, in an appropriate and comfortable position whilst the patient is being

provided with the input movement treatment by the belts, such support of the weight of the patient by the harnesses, being required, for instance, during crawl input movements.

(13) Devices as claimed in Claim 1, and/or Claim 2, and/or Claim 3, and/or Claim 4, and/or Claim 5, and/or Claim 6, and/or Claim 7, and/or Claim 8, and/or Claim 9, and/or Claim 10, and/or Claim 11, and/or Claim 12, in which the design of the harnesses also allows for the deliberate provision of powered or energized cyclic, clockwise and counterclockwise rotation of the patient's head, through suitable, small angles, the rotation of the head being synchronized with the input movements provided to the patient by the belts, this cyclic head rotation being considered to be an essential component of the total input movement, during creep and crawl inputs for instance.

(14) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13, in which the detailed construction of the belts, and the detailed arrangements for stepped or other motions of the belts, take into account that belts must not slip, because such belt slip causes errors in belt positions, and hence, where, special types of flat belts,

- ( sometimes described as timing belts ), are appropriate, since these types of belts can engage with toothed rollers,

- ( a familiar example of engagement being that between a bicycle chain and its associated toothed sprocket wheels ), and thus, where each belt, of an endless construction,- ( in the same way that a conveyor belt, or a car fan belt, or a bicycle chain, is endless ), operates between its own independent set of two toothed rollers, one a driving roller and the other an idler roller, means being provided for maintaining sufficient tension in each belt.

(15) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14, in which all belts are provided with means for attaching or connecting a patient to the belts in a suitable manner, so that, belts are provided with attachment or connecting devices such as loops, and straps, suitable for attaching or connecting a patient's hands, arms, legs and feet to the belts, such loops or straps, as well as the junctions between the belts and the loops or straps, being sufficiently flexible and with sufficient capability of pivoting

or rotating at the junctions, to provide movement of the loops and straps as required for adequate freedom, comfort and safety of the patient, during the input movement treatment imparted to the patient by the belts.

(16) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11

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and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15, in which each belt is capable of being individually and independently programmed, for control of its movement, and for control of rest, where, atleast three different techniques of programming are possible to use, all three techniques being based on already well known techniques used for the programmable control of robots, so that, one or more of these techniques is incorporated in the devices for the remedial treatment of brain injured patients, and where the three techniques are, namely, known as,-

- (i) the Keyboard programming technique, and,
- (ii) the Lead-Through teach programming technique, and,
- (iii) the Walk-Through teach programming technique.

(17) Devices as Claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 6 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16, in which, when applying these devices to the remedial output movement treatment of brain injured patients, the devices can used in ways including,-

(i) the power to the devices being switched off, and the belts being used just as a platform over which the patient moves, to perform outputs, assisted if required, manually, by one or atleast two helpers, the arrangement of harnesses already present on the devices, being used, if required, to support the patient during output movement treatment,

or,

(ii) the devices being selectively power driven during output movement treatment, to provide just sufficient powered assistance to the patient, to complement the patient's own efforts, one of the methods used to achieve this, being the overhead rail system, designed using rails in the form of racks, and the rollers or wheels running on the rail system, in the form of pinions engaging with the rack type rails, and hence, so that, during output movement treatment, the rollers or wheels are suitably power driven, to provide just sufficient assistance to the patient, to complement the patient's own efforts, the patient, in this case, being supported by harnesses that are connected to the system of rollers or wheels,

or,

(iii) unpowered assistance to the patient during output movement treatment, being provided by arranging the roller or wheel system to be attached to one end of a cable or chain that runs respectively over a pulley or sprocket, and the other end of the cable or chain being provided with a mass carrier onto which a

set of masses can be mounted, so that, just sufficient mass can be mounted on the carrier to provide the required assistance to the patient during output movement treatment, and, so that the portion of cable or chain between the roller system and the pulley or sprocket, is horizontal, and, moreover, so that the portion of cable or chain between the pulley or sprocket and the mass carrier, is vertical, and furthermore, so that the mass supplies the driving force derived from acceleration due to gravity, as a result of Newton's Second Law, which states that force equals mass multiplied by acceleration, and yet again, so that the value of the mass placed on the carrier is chosen so as

to provide just sufficient force to the system of rollers or wheels, to complement the patient's own efforts during output

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movement treatment, and where the patient is, in this case, supported by harnesses that are connected to the system of rollers or wheels.

(18) Devices as Claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17, in which the devices are capable of being used for both the input and output remedial movement treatment of brain injured patients, not only for creep and crawl movements, but also for various other classes of movement including walking, and so that the devices can be used for normal, forward direction movements, and also for 'on the spot' type movements, and, where, if required, the devices can also be used for movements in a backward direction.

(19) Devices as Claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17 and/or Claim 18, in which all such devices for the remedial input and output movement treatment of brain injured patients are provided with comprehensive safety features, to protect the patient as well as the operator and helpers, where such protection includes protection to the patient from excessive forces and torques through the incorporation in the devices of special mechanical overload protection facilities, such as slip clutches, and force, position and torque sensing and limiting arrangements, and where, moreover, for safety, the whole device may have to be stopped, since, for example, it may prove dangerous to the patient simply to stop just one belt that is overloaded and to allow the other belts that are not overloaded, to carry on moving,- the danger arising from the type of movement that the belts would provide to the patient, and the resulting possible dangerous posture of the patient, if only one overloaded belt was stopped, and the other belts that were not overloaded, were allowed to carry on moving, and furthermore, where protection is provided to avoid entrapment of limbs and clothing in the devices, that could result in accidents and injuries, and yet further, where means are provided to avoid accidents or injuries from the electrical energy used in the devices.

(20) Devices as Claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17 and/or Claim 18 and/or Claim 19, which are designed for the needs of patients of various sizes, by one of the following means,-

(i) provision of a complete range of sizes of devices, to suit patients that are of small, medium and large size, so that devices are available in models that are, small, or medium or large,

or,

(ii) within any particular model of device within the size range, say for example, a device of small size. provision is made for

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any necessary adjustment to the device, to cater for small patients of various sizes between the upper and lower limits of the small size, such adjustment being effected by using a design of modular construction, which also has features that facilitate the adjustment process, and furthermore, where such modular construction is also used as necessary in order to construct devices to cover the different models within the complete size range, from a rationalized set of elements and modules of construction, so that, this approach of construction is economically attractive in that the number of different components within the inventory of elements and modules required for construction can be kept to a minimum.

(21) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17 and/or Claim 18 and/or Claim 19 and/or Claim 20, in which the design of such devices for the remedial input and output movement treatment of brain injured patients, employs the use of actuators, control systems and sensing systems that are commonly used in robotic and mechatronic systems, such actuators, control systems and sensing systems for the devices being able to include some or all of the following,-

(i) electric motors of various types, such as continuous rotation a.c. motors, d.c. motors of both continuous rotation and stepper variety, and linear motors,  
and,

(ii) electrical solenoids,  
and,

(iii) pneumatic and hydraulic actuators, including motors and cylinders,  
and,

(iv) various commonly applied techniques and components for the control of actuators, including techniques such as open loop and feedback control, pulse width modulation control, and control by the use of neural networks, and components such as optical encoders, switches, and pneumatic and hydraulic control valves,  
and,

(v) systems for both 'internal' and 'external' sensing, in which context 'internal' sensing provides a comparison, for position control purposes of the device, between an actual position and the final, desired, programmed or targetted position, and 'external' sensing provides information to the device, of various factors external to the device, in order to allow the device to react suitably to such external factors.

(22) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17 and/or Claim 18 and/or Claim 19 and/or Claim 20 and/or Claim 21, in which the devices can be used for the remedial input and output movement treatment of brain injured patients, not only for creep and crawl movement treatment, but also for movements such as walking, and postures such as standing, and where, in order to provide for these

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movements and postures additional to creep and crawl movements, powered and/or unpowered components are attached as necessary to the basic frame of the devices, for such special needs, and where such components can be taken off if necessary, when not required, so that, for example, such 'add on', 'take off' components include a ladder placed horizontally overhead, above the patient, so that the patient can grip the rungs of the ladder during movements such as walking with arms raised and postures such as standing with arms raised, and where, furthermore, additional harnesses that are suitable for the support of a patient during movements such as walking, and postures such as standing, are also provided.

(23) Devices as claimed in Claim 1 and/or Claim 2 and/or Claim 3 and/or Claim 4 and/or Claim 5 and/or Claim 6 and/or Claim 7 and/or Claim 8 and/or Claim 9 and/or Claim 10 and/or Claim 11 and/or Claim 12 and/or Claim 13 and/or Claim 14 and/or Claim 15 and/or Claim 16 and/or Claim 17 and/or Claim 18 and/or Claim 19 and/or Claim 20 and/or Claim 21 and/or Claim 22, in which synchronized, powered, clockwise and counterclockwise rotation of the patient's head, through small angles, is required to be provided by a region of the harness that also supports the patient's head, and where such rotation is effected through, for example, the use of actuators, such as electric motors, or electric solenoids, that provide the necessary movement to a particular region of the harness that supports the patient's head, such actuators being controlled so that the clockwise and counterclockwise rotations of the patient's head, through small angles, are synchronized as required, with the movements provided to other parts of the patient's body by belts existing in the device.