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**CEREBRAL PALSY AND RHIZOTOMY:
A TEN YEAR FOLLOW-UP STUDY WITH GAIT
ANALYSIS**

by

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**A thesis presented to the University of Cape Town in partial fulfillment
of the requirements for the degree of Master of Science (Med) in
Biomedical Science**

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ABSTRACT

In 1985, a cohort of 14 children with cerebral palsy underwent a neurosurgical procedure — selective posterior rhizotomy — in an effort to reduce their spasticity. They were part of a prospective study in which their gait was analysed before surgery and at one and three years post-operatively. In 1995, ten years after surgery, there were important questions that needed to be addressed: would their gait be different from the findings before surgery and three years after surgery and how would they compare with age-matched normal subjects? Three of the original subjects were lost to follow-up and 11 were invited to participate in this long-term study. Their ages ranged from 12 to 24 years at the time of evaluation.

Their gait was studied in the sagittal plane by taping retro-reflective markers onto the greater trochanter, lateral femoral epicondyle and lateral malleolus and having the subjects walk in a direction perpendicular to a video camera recording their gait. The data were digitised and analysed making use of custom written software and all relevant gait parameters were calculated. The parameters evaluated were the ranges of motion and mid-range values of the knee and thigh, and the spatial-temporal parameters, namely cadence, stride length and velocity. Data were also obtained from twelve age-matched normal control subjects.

The ten year results were compared to the pre-operative data, the data obtained from the three year study and the normal controls. A statistical analysis was performed on these parameters by using multiple analysis of variance (MANOVA) and *post hoc* comparisons were performed with a Scheffé test and a significance level set at $p < 0.05$. Results indicated that after ten years, the joint ranges of motion and mid-range values did

not differ significantly from the normal values. The values also did not vary significantly from the values obtained in the three year follow-up study, suggesting that functional changes acquired due to rhizotomy were of long term duration. The spatial-temporal parameters, however, did differ significantly from the normal range. Although this finding may have been influenced by the environment and subject motivation, the reduced cadence and stride length meant that the cerebral palsy subjects walked slower than their normal counterparts.

This project, while confirming the results of the previous subjective studies, provides the first long-term objective data that establishes the effectiveness of selective posterior rhizotomy in improving and maintaining locomotor function for children with spastic cerebral palsy.

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LIST OF ABBREVIATIONS

A	Area
df	Degrees of freedom
EMG	Electromyography
I.Q.	Intelligence Quotient
KMRV	Knee mid-range value
KROM	Knee range of motion
MS	Mean Square
n.a.	Not Available
No	Number
P	Perimeter
PC	Personal Computer
Pre-Op	Pre-Operative
Post-Op	Post-Operative
S.D.	Standard Deviation
TROM	Thigh range of motion
TMRV	Thigh mid-range value
VCR	Video Cassette Recorder
vs	versus
yr	year

CHAPTER ONE

INTRODUCTION

Cerebral palsy is a relatively common disorder affecting one in two hundred children world-wide. It is the result of a nonprogressive pre- or ante-natal insult to the brain which may originate either from an external traumatic injury or an abnormal development of the nervous system in the foetus. It was first associated with difficult birth by William John Little and was known as Little's Disease for decades. The term *cerebral palsy* was first applied in 1888 by Sir William Osler in his review of 151 cases of cerebral palsy (Blasco, 1991).

Cerebral palsy is typically characterised by the fact that afflicted children all have problems with motor development. Many other disabilities may be associated with the motor disorder including varying degrees of mental handicap, speech problems and epilepsy. Classification may be made more specific depending upon the physiological type and topography of cerebral palsy. The main types of cerebral palsy seen are the *spastic*, *athetoid* and the *ataxic* types.

The *spastic* type results from insults to the motor cortex. The typical neurological characteristics observed are hypertonicity of the "clasp knife" variety, increased tendon jerks and associated clonus. The subject exhibits abnormal postures and laboured voluntary movements.

Subjects with the *athetoid* type of cerebral palsy tend to have normal intelligence, though mental defect does occur. The athetoid type of cerebral palsy is normally characterised by involuntary writhing movements. Voluntary motion is possible and may be initiated, but very often this becomes partially or wholly disrupted by involuntary movements, making motion uncoordinated. There is also a marked lack of fine movement control and weakness. Athetoids tend to change with time; they may be floppy in infancy and only exhibit the

involuntary movements when they reach two to three years of age. Adult athetoids do not appear hypotonic but have muscle tension which increases in an effort to control voluntary movements (Levitt, 1977).

The *ataxic* type of cerebral palsy describes a disturbance of balance and poor fixation of the head, trunk, shoulder and pelvic girdles. Voluntary movements are present but clumsy and uncoordinated. Intelligence is often low and visual learning and perceptual problems occur.

Topographically, cerebral palsy may be classified into *quadriplegia* (involving all four limbs), *diplegia* (involving all four limbs but with legs more severely affected), *paraplegia* (involving both legs), *triplegia* (involving three limbs), *hemiplegia* (where one side of the body is affected) and *monoplegia*, a rare case where only one limb is affected.

Cerebral palsy may be brought about by a number of pathological conditions, the more noteworthy of these being ventricular haemorrhage, scarring of the basal ganglia, focal infarction brought about by disease or mechanical trauma, and necrosis of white matter (Rymer, 1991). Another cause, Rh incompatibility between the mother and child which leads to kernicterus, is increasingly rare nowadays.

Spasticity may be defined as a motor disorder characterised by a velocity dependent increase in tonic stretch reflexes with exaggerated tendon jerks resulting from hypersensitivity of the stretch reflex. Of the three types of cerebral palsy described above, the spastic variety is the most common and has been extensively studied (Vaughan *et al.*, 1989). Spasticity is caused by an increase in the motoneural excitability due to a sustained or tonic descending depolarising input to spinal motoneurons or an increase in the response elicited by

muscle stretch. Due to the damage of the cerebral cortex there is decreased inhibition and the only active circuit in effect is the spinal reflex arc. Balance between facilitation and inhibition is upset due to absence of stimuli from the cerebral cortex, with the result that affected muscles acquire a hypertonic characteristic of the “clasp-knife” variety, accompanied by rigidity (Rymer, 1991).

Spasticity may be eased by non-surgical as well as surgical techniques. Non-surgical techniques in the form of drug therapy using muscle relaxant agents such as *Baclofen* (Lioresal), and *Diazepam* (Valium) (Blackman *et al.*, 1991) or *Botulinum toxin A* (Botox) (Koman *et al.*, 1993), offer short term relief from spasticity but costs can be prohibitive in the long term. Orthopaedic surgical techniques currently in use include lengthening or release of muscles and tendons, and procedures involving the bones. These procedures, however, do not reduce spasticity *per se* and are performed only to minimise developmental deformities associated with cerebral palsy such as hip subluxation, knee flexion contractures, and spastic equinus deformities of the foot and ankle (Vaughan *et al.*, 1989).

A neurosurgical technique that has gained popularity since the early 1980s is *selective posterior rhizotomy*. The first posterior root rhizotomy operation was performed as far back as 1913 by Foerster as a cure for spasticity with dramatic results (Foerster, 1913). The technique was largely ignored for the next five decades due to the fact that the excision of the entire set of nerve roots (from L2 to S1, excluding L4) was extensive, which meant that sensation, joint position sense, bladder and bowel control were seriously impaired.

In 1976, the Italian neurosurgeon Fasano modified the technique by selecting only those rootlets that gave rise to abnormal responses and sectioning them at the level of the conus medullaris (Fasano *et al.*, 1976). Though sensory loss was minimised, bladder and

bowel continence still posed a problem as identification of the individual rootlets at this level was difficult. In 1982, Peacock at the University of Cape Town further modified the procedure by shifting the site of detachment near the exit of the individual nerves at their respective foramina where identification of the individual rootlets was easier (Peacock and Arens, 1982). This helped in limiting loss of bladder and bowel control while still maintaining good results for reduction of spasticity.

Selective posterior rhizotomy is performed under endotracheal anaesthesia without administration of muscle relaxants. A laminectomy is performed from L2 to S5, exposing the anterior and posterior roots from L2 to S2. The posterior root is identified and separated from the anterior root after the dura is opened. The posterior root is then subdivided into 8 to 10 rootlets with a microprobe and is stimulated with electrodes. A test stimulus is applied gradually increasing the voltage until a distinct muscle contraction occurs. A stimulus at 50 Hz is applied at the predetermined voltage for one second. Electromyographic (EMG) recordings from the leg muscles are observed for any abnormal responses and if any are observed, that particular rootlet is severed (Abbott *et al.*, 1990).

Approximately 200 children have been operated upon in Cape Town since 1982, although not all were ambulatory. While gait analysis was not performed pre-operatively on the earliest candidates for this procedure, a prospective study was done on a cohort of 14 patients who underwent this procedure in 1985. A gait analysis follow-up of these patients was performed one year after surgery (Vaughan *et al.*, 1988), and was repeated two years later as a three year follow-up study (Vaughan *et al.*, 1991a).

The importance of gait analysis in ambulatory patients with cerebral palsy cannot be emphasised enough for this is an established, objective way to evaluate the success of any

orthopaedic or neurosurgical operation performed to reduce spasticity in terms of the functional range of motion possible for the patient. The three year follow-up study of Vaughan *et al.* (1991a) clearly indicated that patients who underwent this procedure had a significant improvement in that their knee and thigh ranges of motion approached or exceeded normal values (Figures 1.1 and 1.2) and they also showed an improvement in posture control (mid-range values). Note that because they used only 3 markers (hip, knee and ankle), Vaughan *et al.* (1991a) reported *thigh* angles (orientation of the thigh relative to the vertical reference), rather than *hip* angles which is more common in gait studies. Since this thesis is essentially a follow-up to the work of Vaughan *et al.* (1991a), the same naming convention is adopted throughout.

A ten year follow-up study was done on 110 patients who underwent the procedure between 1981 to 1991 and long term tone reduction was observed in 95% of the cases (Peter and Arens, 1993). However, the evaluations were based on subjective analysis, and there has been no objective long term study carried out elsewhere in the world. South Africa, being the first country in the world where selective posterior rhizotomy was done on a large scale, has some of the earliest beneficiaries of this procedure and hence it is possible to conduct the first objective follow-up gait analysis study. Almost all the patients who underwent this surgery in the mid-1980s were children in the age group of 2 to 14 years. A follow-up study of their gait ten years later would probably yield crucial information on how the surgical procedure has benefited their ambulatory capacity as adolescents and young adults. The study proposed for this thesis would therefore be extremely beneficial to clinicians as it could provide concrete

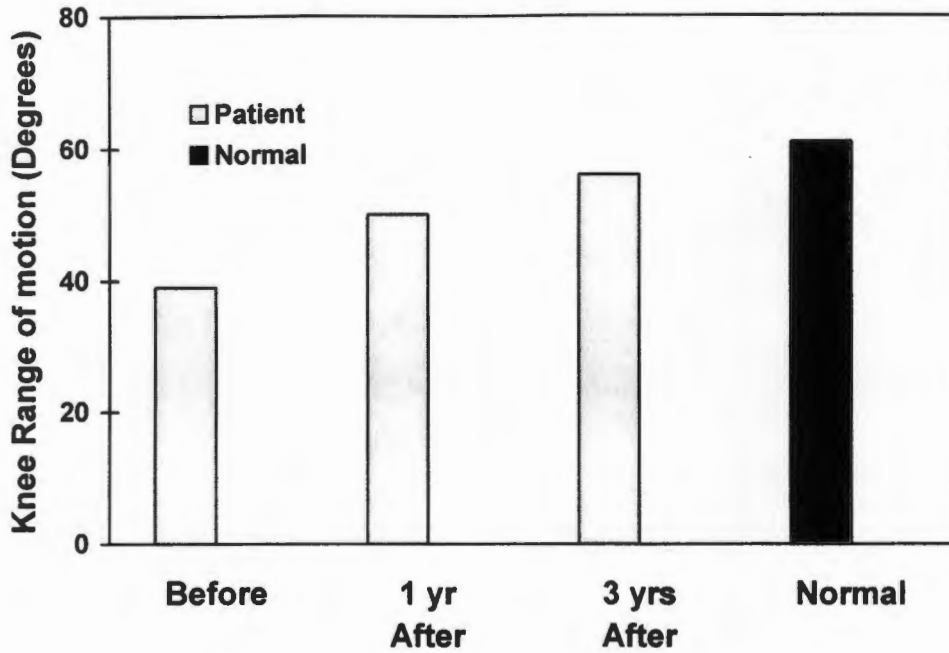


Figure 1.1 Range of motion for the knee in rhizotomy patients before surgery and 1 and 3 years after surgery (Vaughan *et al.*, 1991a)

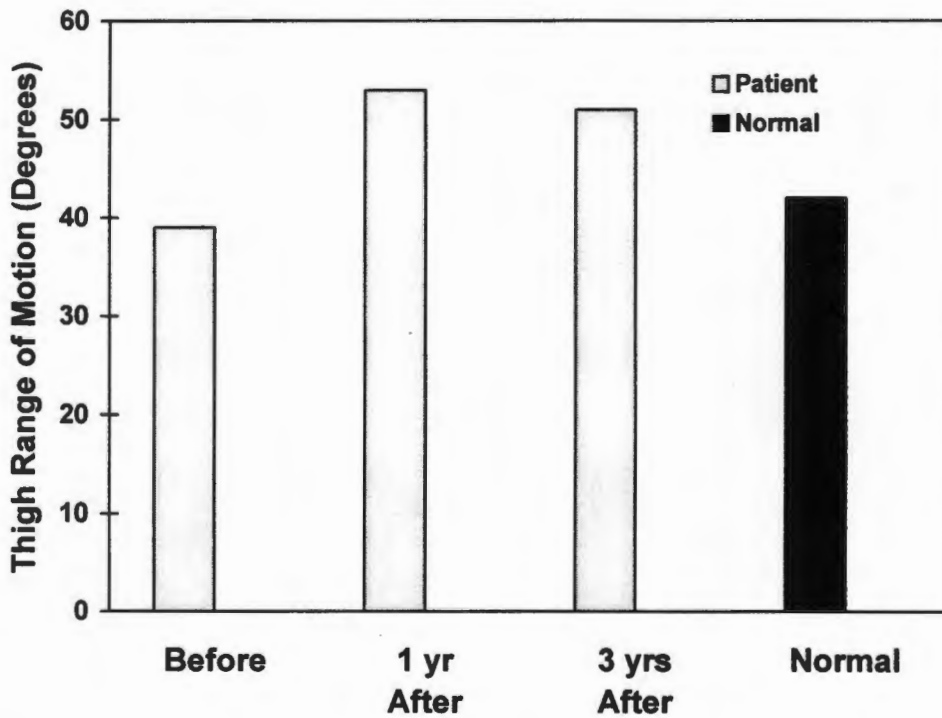


Figure 1.2 Range of motion for the thigh in rhizotomy patients before surgery and 1 and 3 years after surgery (Vaughan *et al.*, 1991a)

evidence of the potential long term advantages of recommending selective posterior rhizotomy to patients with spasticity.

This study, a ten year follow-up on the one year and three year post-operative studies conducted by Vaughan *et al.* (1989,1991a), will compare data obtained from the earlier studies as well data obtained from normal subjects in the same age range. The method proposed to carry out this study is to videotape the subjects to obtain two dimensional data of their gait. The subjects will have reflective markers taped onto their lower limbs, the positions being the greater trochanter, the lateral epicondyle of the femur and the lateral malleolus on the fibula and they will be videotaped in the sagittal plane. The data obtained from the videotapes will be digitally analysed by means of custom-written software. The following hypotheses are proposed as the basis for the project:

- (1) There will be a significant increase in range of motion at the hip and knee joints when ten year post-operative data are compared with the pre-operative data.
- (2) There will be no significant difference in joint ranges of motion when three and ten year post-operative data are compared.
- (3) There will be no significant differences in joint ranges of motion and spatial-temporal parameters (stride length, cadence and velocity) when ten year post-operative data are compared with age-matched normals.

CHAPTER TWO

LITERATURE REVIEW

The following pages provide a brief literature survey of research that has been conducted in the areas of cerebral palsy and associated spasticity, selective posterior rhizotomy, and gait analysis.

2.1 CEREBRAL PALSY AND SPASTICITY

Cerebral palsy is the term applied to a group of conditions characterised mainly by motor disability resulting from a non-progressive, permanent insult to the developing nervous system. The cause of insult, which may be pre- or ante-natal, can result from damage to an otherwise normally developing system or can be due to the abnormal development of the nervous system itself (Blasco, 1991). Spasticity is a consequence of an insult to the motor control area of the cerebral cortex.

2.1.1 Historical Background

Cerebral palsy, or Little's disease as it was initially known, was first described by an English orthopaedist, William J. Little, who attributed it to difficult birth. He put forward the hypothesis that spasticity was due to neonatal brain damage. The term *cerebral palsy* itself was coined by Sir William Osler in 1888 in his review of 151 cases, most of whom were subjects with spastic diplegia. Sigmund Freud in 1897 associated spastic diplegia with premature birth in his treatises on the classification of cerebral palsy (Blasco, 1991). Freud

also was the first to emphasise that observed symptoms could arise from a variety of causes and that the disorder itself could be classified into subgroups or types (Hardy, 1983).

2.1.2 Classification of Cerebral Palsy

It is difficult to classify cerebral palsy precisely into individual categories but three distinct physiological types may be seen. These are the spastic (80% of all cerebral palsy cases), the athetoid (15%) and the ataxic (5%) types, though very often cerebral palsy exists as a combination of two types (Eiben and Crocker, 1983).

The spastic type of cerebral palsy is characterised by varying levels of intelligence, usually tending to be lower than in athetoids. Sensory loss may occur and growth of the limb on the affected side is usually lower than that on the unaffected side in hemiplegics. These subjects may experience perceptual problems especially in relation to space. Epilepsy is more common than in athetoids. Motor characteristics include hypertonicity of the “clasp knife” variety in the affected muscles. When these muscles are stretched, they respond in an exaggerated manner by contracting and blocking the movement. Other characteristics include increased tendon jerks and clonus. Patients with spastic cerebral palsy also display abnormal postures associated with the anti-gravity muscles, namely the extensors in the legs and flexors in the arm. This is due to overactivity of spastic muscle groups in which the antagonists are weak or cannot overcome the tight pull of the spastic muscles to correct postures. Fear, excitement or anxiety may bring about changes in hypertonicity and posture due to increased muscle tension. Voluntary motion, though laboured, is present (Levitt, 1977).

The athetoid type of cerebral palsy is characterised by uncontrollable purposeless movements which may be writhing, jerky, tremor, swiping or totally random patterns. This

kind of motion is increased by excitement, insecurity and decreased by fatigue, fever, drowsiness or if the subject's attention is deeply held. Voluntary motion is possible with an initial delay before the motion is begun. The involuntary movement may partially or entirely disrupt willed motion, making it appear uncoordinated. There may be fluctuations of muscle tone occurring with swings in mood or emotions. Athetoids tend to change with time, remaining floppy in infancy and exhibiting the characteristic involuntary movements only when they reach 2 to 3 years of age. Adult athetoids tend to display muscle tension which seemingly increases in an effort to control involuntary movements. Due to minimal damage to the cerebral cortex. People with athetosis tend to possess normal or even higher intelligence compared to spastics though mental defect does occur. They are often observed to have "drive" and outgoing personalities (Levitt, 1977).

The ataxic type of cerebral palsy is characterised by low intelligence with visual, auditory and perceptual problems. People with ataxia display a poor fixation of the head, trunk, shoulders and pelvic girdle. Voluntary movements are clumsy and uncoordinated. The affected individual tends to over-reach or under-reach for an object, suffering from dysmetria and accompanied sometimes by intention tremors. People with ataxia usually display hypotonia and a purely ataxic case is rare (Levitt, 1977).

2.1.3 Neuroanatomy and Topographical Classification

Stretch receptors or the muscle spindle fibres located within skeletal muscle are responsible for sending impulses that regulate muscle tension via the spinal reflex arc. The afferent impulses are sent from the muscle spindles to the spinal cord via the posterior roots and activate the anterior horn cells that innervate the extrafusal muscle fibres. The length of

these fibres is controlled by the gamma anterior horn cells. An example of this is the knee jerk reflex (Hardy, 1983). The descending corticospinal tracts from the motor cortex exert an inhibitory influence on the anterior horn cells and damage to these tracts leaves only the facilitatory influence of the alpha motor neuron, leading to the classical picture of spasticity (Peacock and Eastman, 1981). The cell bodies of the corticospinal axons, known as the pyramidal cells, reside in the precentral gyrus of the cerebral cortex. The topographical arrangement of these cells relative to the muscle groups they innervate is shown in Figure 2.1. The axons of the cells deep within the longitudinal fissure influence the alpha neurons that innervate the feet. Progressively upwards over the lateral surface of the precentral gyrus, the cell bodies provide innervation to the legs, torso, arms and hands. Consequently, insult to the various areas of the precentral gyrus results in the topographical distribution of neuromotor impairments in cerebral palsy shown in Figure 2.2 (Hardy, 1983). Topographically, cerebral palsy may be classified into *quadriplegia* (where all four limbs are affected), *diplegia* (involvement of four limbs with the legs being more affected than the arms), *paraplegia* (involvement of both legs), *triplegia* (involvement of three limbs), *hemiplegia* (involvement of one side of the body) and *monoplegia*, a rare case where one limb is affected (Levitt, 1977).

2.1.4 Neuropathology of Cerebral Palsy

In discussing the causes of cerebral palsy, it is possible to classify these into developmental abnormalities and traumatic injuries inflicted on the normally developing brain. Some of the more important encephaloclastic processes that give rise to cerebral palsy are the following:

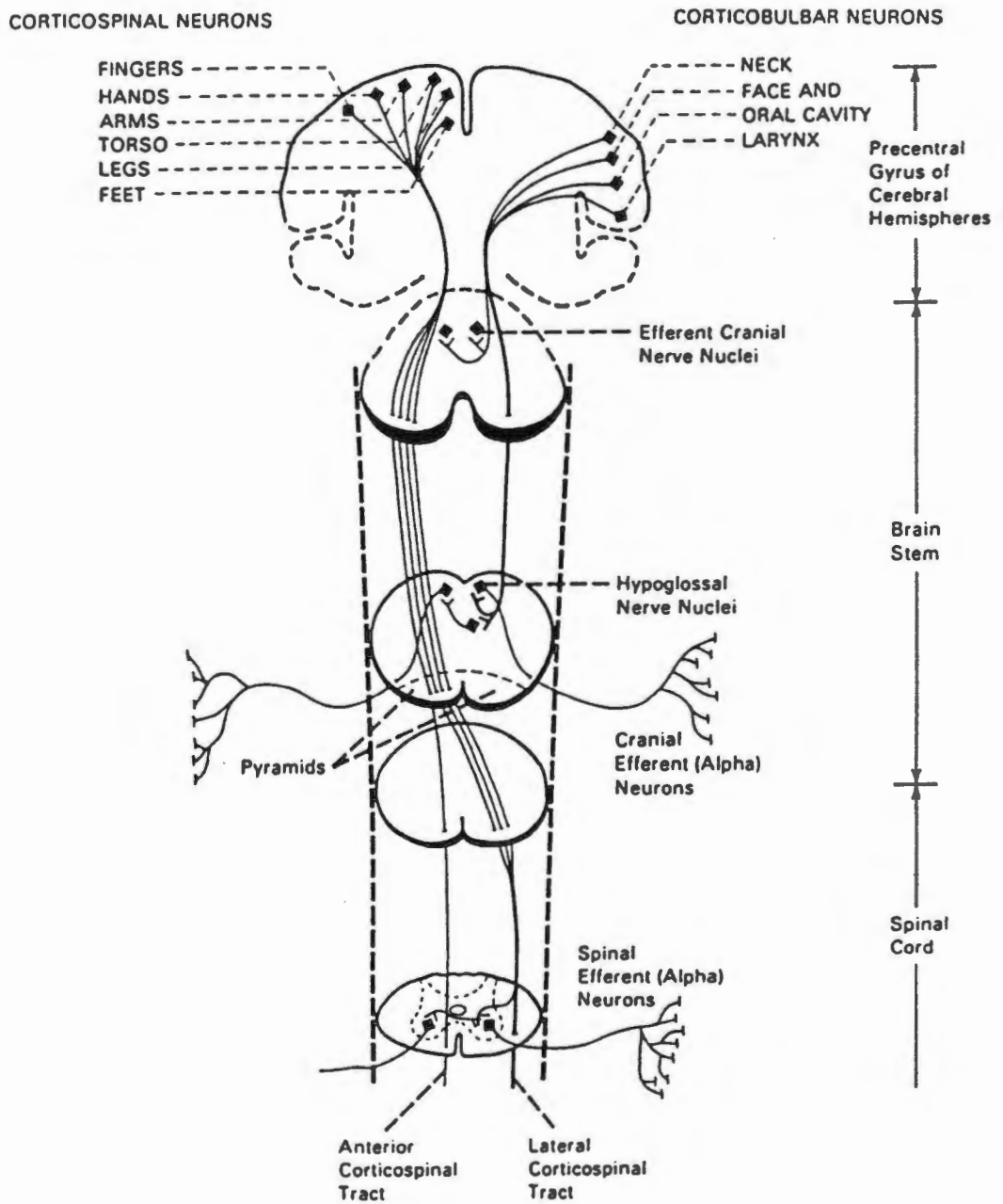


Figure 2.1 Topographical distributions of neurons in the precentral gyrus and corresponding innervation of muscle groups (Hardy, 1993)

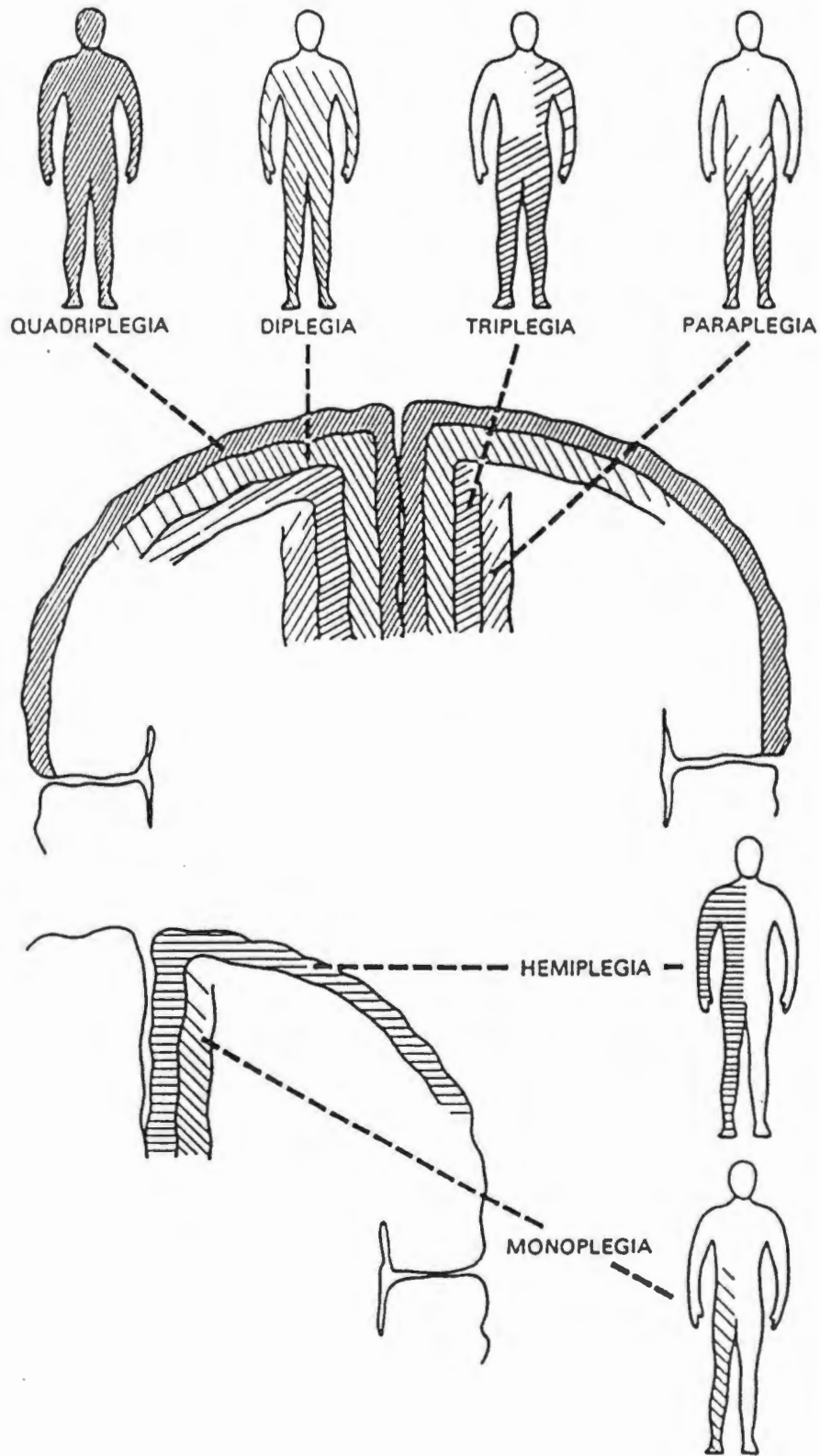


Figure 2.2 Topographical distribution of neuromotor impairments in spastic cerebral palsy (Hardy,1983)

1. Kernicterus: caused by the presence of bilirubin in the blood, which can infiltrate the nervous system of a newborn, due to Rh incompatibility factors between the mother and child. Some clusters of neurons are more susceptible to bilirubin damage than others, with the result that a child with cerebral palsy due to kernicterus is characterised by athetosis and high frequency hearing loss (Hardy, 1983). This cause, however, is becoming increasingly rare due to early detection and prevention of complications arising from Rh incompatibility.

2. Periventricular Leukomalacia: a consequence of ischaemia in the vulnerable arterial zones close to the ventricular wall, this is seen as necrotic patches in the periventricular white matter adjacent to the external angles of the lateral ventricles. The lesions may encroach into periventricular cavities surrounded by glial scar tissues with calcified fibres, resulting in thinning of the white matter in the corpus callosum and centrum semi ovale and also in the expansion of the lateral ventricles. Periventricular leukomalacia may be the most common cause of spastic diplegia since the pyramidal tract fibres from the lower extremities sweep most closely past the lateral ventricles before turning down into the internal capsule (Blasco, 1991). This has been verified by conducting MRI studies of patients with spastic cerebral palsy who have undergone selective posterior rhizotomy (Park *et al.*, 1989).

3. Status Marmoratus: this refers to the scarring of the basal ganglia. These lesions are bilateral, symmetric and affect the thalamus, putamen and the caudate nucleus most severely. The choreo-athetoid type of cerebral palsy is a classic result of this syndrome. Since the cortex is usually spared, intelligence may be normal or even superior (Blasco, 1991).

4. Intraventricular or sub-ependymal haemorrhage: it originates in the germinal matrix, a poorly supported but well vascularised zone adjacent to the ventricular wall and may bleed into the ventricular space. The haemorrhage is seen as a small lake of blood in the subependymal germinal matrix near the caudate nucleus. Subependymal haemorrhage is fatal in many cases and those who survive are afflicted by hydrocephalus and spasticity (Banker and Bruce-Gregorios, 1983).

Additional causes of cerebral palsy are focal infarctions which may be brought about by mechanical injuries, infections or vascular defects such as a faulty distribution of blood vessels leading to ischaemia. Developmental abnormalities resulting in cerebral palsy usually occur due to some disruption in the migratory process of neuroblasts from the neuromedullary zone to their permanent positions, resulting in the depletion of nerve cells in the cortex. Developmental abnormalities may be caused by drugs like Thalidomide and Diphenylhydantoin (Dilantin), alcohol and ionizing radiation. Infections such as Rubella and Herpes simplex, if contracted by the mother during this critical phase of neural development in the foetus, may also lead to the arrest of neural migration (Banker and Bruce-Gregorios, 1983).

2.1.5 Surgical and Non-Surgical Interventions

Spasticity may be alleviated using both surgical and non-surgical techniques. Non-surgical methods such as physiotherapy and occupational therapy aim to reduce spasticity by teaching the patient new postures and movement patterns. Administration of physiotherapy differs with age (Cassidy-Conway and Zawacki, 1983), and may have to be continued indefinitely in the form of direct and indirect care. There has been no direct evidence for the efficacy of physiotherapy alone in the management of cerebral palsy though when coupled

with surgical techniques as a part of post-operative care and rehabilitation, the administration of physiotherapy is indispensable (Campbell, 1991).

A number of muscle relaxant drugs have been used to reduce spasticity, albeit with temporary relief. The drugs, which are GABA (Gamma-aminobutyric acid) analogues, work by inhibiting the release of excitatory neurotransmitters from the terminal synaptic knobs of the primary afferent fibres. Some of the most commonly used drugs are: (1) Diazepam, a GABA analogue which inhibits the release of excitatory neurotransmitters and thereby acts as a muscle relaxant; (2) Dantrolene, which acts directly on skeletal muscle by inhibiting the release of calcium from the sarcoplasmic reticulum and thereby decreases the force of muscle contraction and produces muscle weakness (Park and Owen, 1992); and (3) Baclofen, another GABA analogue, which inhibits transmitter release by competitive inhibition of neurotransmitters at the spinal level (Blackman *et al.*, 1991). However, the oral administration of antispastic drugs is ineffective in reducing spasticity, due to the limited ability of the drugs to penetrate the blood-brain barrier (Park and Owen, 1992). Another procedure recently introduced is the administration of Botulinum-A toxin (Botox) injections directly into the affected muscles. This reduces overactivity in spastic muscles for about 3 to 6 months with no apparent adverse side effects (Koman *et al.*, 1993).

Surgical methods currently in use may be classified into orthopaedic and neurosurgical procedures. Orthopaedic surgery includes three types of surgery on muscles and tendons, namely: release, lengthening and transfer (Moseley, 1991). Appropriate surgery is performed depending upon the affected muscle. There are four common procedures. First, distal hamstring lengthening surgery aims to eliminate crouched gait pattern, and may minimise internal rotation gait (Root, 1991). This procedure may be

performed in conjunction with rectus femoris transfer which helps to reduce excessive knee flexion in rapid gait, thereby increasing the range of motion (Gage, 1991b). Second, Achilles tendon lengthening corrects ankle equinus (Rosenthal and Simon, 1991). A variation of this procedure is the gastrocnemius-soleus lengthening which is done when the soleus muscle does not display significant contracture (Simon and Ryan, 1991). Third, varus foot deformities are treated by split anterior tibial tendon transfer, a procedure by which the lateral half of the anterior tibial tendon is moved to the cuboid, creating a balanced yoke on the foot and thereby neutralising the varus pull of the anterior tibial tendon (Roehr and Lyne, 1991). Finally, deformities of the hindfoot are treated by a split posterior tibial tendon transfer (Green, 1991).

Surgery may also be performed at the hip to alleviate the consequences of cerebral palsy, namely complications like hip dislocations arising due to a combination of factors such as spastic muscle imbalance. Orthopaedic procedures performed include total hip arthroplasty (Root *et al.*, 1986), which is most effective on patients with no evident contralateral subluxation or dislocation of the hip (Bleck, 1987), resection arthroplasty to treat total body involved patients in whom there is severe erosion of the articular cartilage and gross incongruity of the femoral head and acetabulum as a consequence of prolonged dislocation (Bleck, 1987; Sherk *et al.*, 1983; Koffman, 1981), and femoral and pelvic osteotomies (Tylkowski *et al.*, 1980; Sherk *et al.*, 1983).

Although alternative techniques such as selective peripheral neurotomies where peripheral nerves are interrupted using microscopic techniques have been partially successful (Sindou *et al.*, 1985), the most prevalent neurosurgical procedure currently performed for the reduction of spasticity is selective posterior rhizotomy.

2.2 SELECTIVE POSTERIOR RHIZOTOMY

2.2.1 Historical Background

The original concept of rhizotomy or “cutting roots” is credited to Dr. C.L Dana of New York who recommended this operation, and it was first performed by Robert Abbe in 1888 for the relief of pain in a case of ascending neuritis (Foerster, 1913).

Posterior (sensory) root rhizotomies were first performed by Dr. Otfried Foerster, a German neurosurgeon, in 1908. He described 159 cases of which 88 were cases of “congenital spastic paraplegia” (Foerster, 1913). The technique he adopted was division of the entire posterior sensory roots from L2 to S2, excluding either L4 or L5 to preserve knee extensor tone. Foerster distinguished the anterior and posterior nerve roots and identified the roots associated with knee extensors via electrical stimulation (Peacock and Staudt, 1990). He also emphasised the identification of spastic cases as opposed to athetosis and paralysis and reported improved results in patients with lower extremity involvement. These criteria are still very much in consideration when selecting patients in the current era (Oppenheim *et al.*, 1991). The procedure fell into disuse over the next six decades following Försters pioneering work owing to difficulties with sensory loss due to extensive and indiscriminate sectioning of the posterior roots. During this period, spasticity was treated by anterior root rhizotomy which brought about muscle atrophy, or by destructive procedures like cordotomy or myelotomy (Yamada *et al.*, 1976), in which the side effects were often greater than their benefits (Albright, 1988)

Gros and associates (1967) revised Förster’s procedure by sectioning only a fraction of the rootlets, and thus preserving sensation. They further refined the technique by

electrically stimulating each of the rootlets, thereby mapping out those related to essential muscles like the quadriceps, abdominal and pelvic supporters which were left intact. Those muscles that showed abnormal action in the EMG recordings, and were thought to cause spasticity, were then “released” by sacrificing their respective sensory rootlets (Gros, 1979).

Fasano and associates (1976) discovered that certain rootlets, when stimulated with impulses of a certain frequency, responded with a brief localised contraction whereas others showed a continuous prolonged contraction which spread to other muscles, an abnormal phenomenon linked with those muscles associated with spasticity. These rootlets were then sectioned. This technique relieved spasticity without compromising sensation. It was later applied to a group of adults suffering from multiple sclerosis and spinal cord injuries with positive results (Laitinen *et al.*, 1983).

The Fasano procedure, initially performed in the region of the conus medullaris, was modified by Peacock in 1981 (Peacock and Arens, 1982). He shifted the site of rhizotomy to the region of the cauda equina, thus facilitating easier separation of the anterior and posterior roots and identification of individual rootlets. This is the technique that has been widely adopted for selective posterior rhizotomy today.

2.2.2 Patient Selection

The primary objectives of selective posterior rhizotomy are to improve locomotion function in a spastic individual or to ease daily handling and care of the invalid in the case of a non-ambulatory child with severe quadriplegia. Candidates may either be classified as ambulators who may be capable of maintaining and improving functional abilities upon alleviation of spasticity, or those patients who have been severely affected by cerebral palsy

to the extent that they are non-ambulatory and care taking becomes difficult. Most patients in this second category tend to be intellectually handicapped (Peacock and Arens, 1982).

The ideal candidate for selective posterior rhizotomy would be a mobile and motivated child with normal or near-normal intelligence who is attempting to improve his/her gait pattern (Oppenheim *et al.*, 1991). Although these children are usually less than 12 years of age, the procedure has been performed on teenagers, yielding a reduction in tone with positive functional outcomes in 77% of the cases (Peter and Arens, 1994). Selection criteria for the procedure include; (1) Premature birth. These children are usually identified by the age of one year and display an initial hypotonicity that progresses to pure spasticity; (2) Good underlying strength, along with trunk and motor control. Some children use their spasticity to compensate for lack of support from the anti-gravity muscles and rhizotomy in such a case could be detrimental; (3) Absence of rigidity, dystonia, athetosis and ataxia. Since these conditions are not brought about by damage to the motor cortex, patients suffering from any of these conditions will not usually benefit from rhizotomy (Oppenheim *et al.*, 1991).

Evaluation of trunk musculature, head control and equilibrium responses are done using the Rancho Los Amigos hospital test of upright motor control (Montgomery *et al.*, 1983). Prospective candidates for rhizotomy are evaluated thoroughly by a team which normally consists of a paediatric neurologist, a paediatric neurosurgeon, an orthopaedic surgeon, a paediatric psychologist, paediatric physiotherapists and occupational therapists (Abbott *et al.*, 1989). Their task is to determine crucial factors such as compromised muscle groups and to give the surgical team complete detailed pre-operative information on which the eventual pattern of surgery will be based.

2.2.3 Operative Procedure

The patient is placed prone on the operating table with bolsters under the pelvis and chest to allow free movement of the abdominal wall. This also prevents epidural vein distension and reduces bleeding (Peacock and Staudt, 1990). A general endotracheal anaesthesia is administered using agents such as halothane, fentanyl or nitrous oxide without the use of muscle relaxants which might affect intra-operative EMG monitoring (Oppenheim, 1990). Using the posterior superior iliac spines as reference, the lumbosacral spinous processes are marked to the level of the L4 spine. A midline laminectomy (in which case a sub-periosteal dissection is used to allow for bone formation from the intact periosteum after closure) or laminotomy (where the bone is sutured back into place) is then performed from L2 to L5 (Peacock and Staudt, 1990), though some surgeons include L1 as well (Gaskill *et al.*, 1992). The addition of this level carries a certain amount of risk since it ventures close to the thoracic region. On the other hand, Lazareff *et al.* (1990) have shown positive results with a L5 to S1 laminectomy.

Before the dura is opened, care should be taken to ensure haemostasis in the muscular layer since the presence of blood in the spinal canal can impede the procedure by making root identification and management more difficult. This also occurs when the dura is accidentally opened during laminectomy, causing blood to leak into the sub-arachnoid space and the loss of cerebro-spinal fluid, leading to the adherence of clots to the roots and possible spinal canal collapse (Schijman *et al.*, 1993). Once the dura is opened, the nerve root levels are confirmed using electrical stimulation by eliciting motor responses from the anterior roots of S1 and S2. The anterior roots are then separated from the posterior roots from L2 to S1 with the help of a magnifier. The threshold voltage is determined by

stimulating the posterior root of L2 using microsurgical blunt hook electrodes. The posterior root is then subdivided into a number of rootlets, usually about 40 to 50 for a typical bilateral case. Each one of these is stimulated with a 0.1 ms pulse at 10 V. The voltage is gradually increased until a response is seen on the EMG. The EMG response to a non-sinusoidal stimulus of 50 Hz is noted. Roots giving rise to abnormal patterns such as the one shown in Figures 2.3 (a-c) are then sacrificed, while those showing normal responses (Figure 2.3 d) are spared. Examples of abnormal responses as defined by Fasano *et al.* (1976) are: (1) an incremental amplitude EMG response; (2) muscles responding to stimulation of nerve roots not connected to it; and (3) a continued tetanic contraction response even after the stimulus is removed (McLaughlin *et al.*, 1994).

Variations on this procedure, such as shifting the site of excision just caudal to the conus medullaris (Park *et al.*, 1993), have been proposed with the claim of reducing motor weakness in intensity after selective posterior rhizotomy. However sufficient evidence is still lacking to support this approach. Inclusion of the S2 rootlet (involving plantar flexion), though not performed in all cases due to possible complications with incontinence, has been shown to reduce plantar flexor spasticity significantly (Lang *et al.*, 1994).

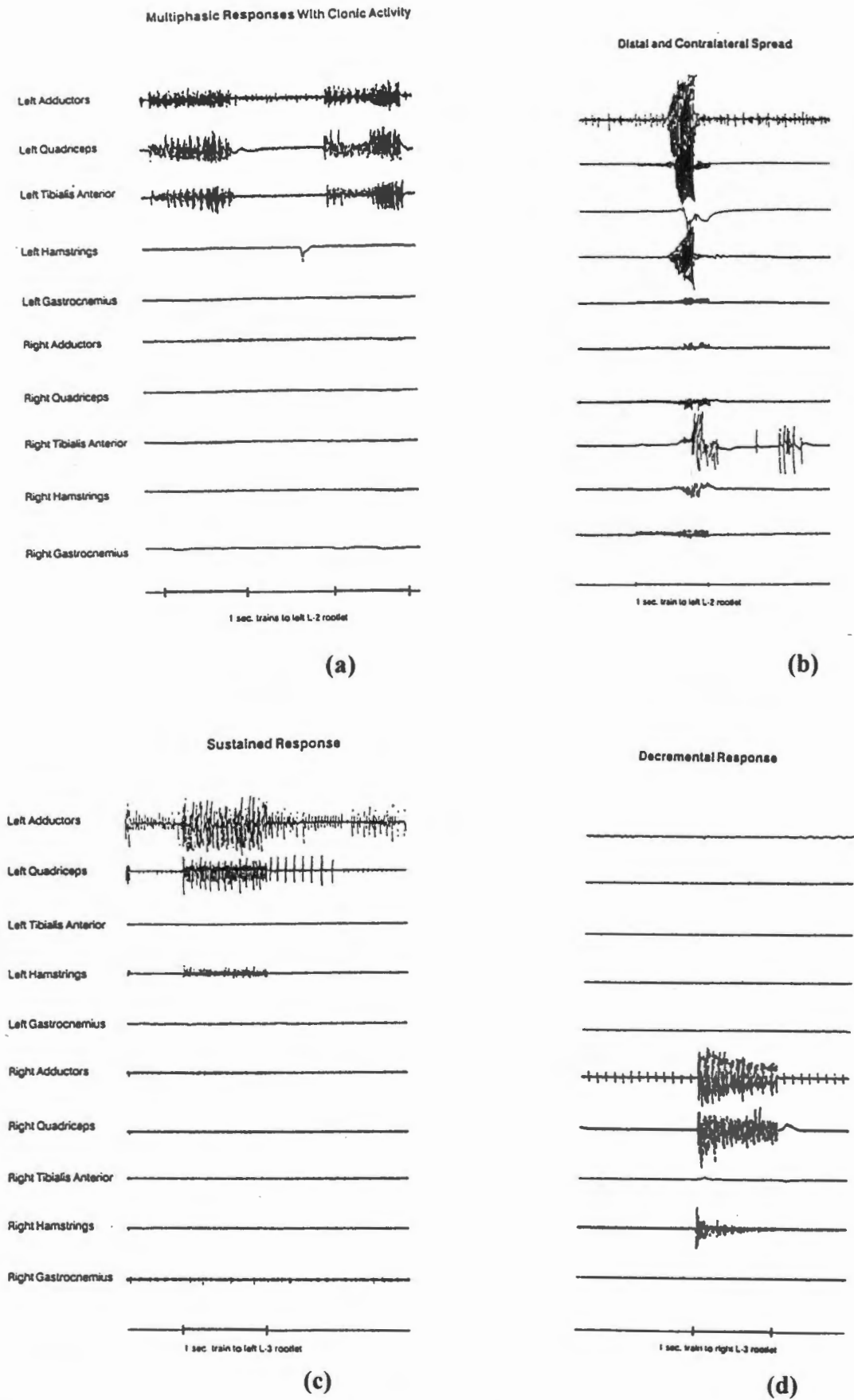


Figure 2.3 Intra-operative EMG responses during rhizotomy: (a) multiphasic responses with clonic activity; (b) distal and contralateral spread; (c) Sustained response; (d) Decremental response (Oppenheim,1990)

2.2.4 Outcome

Selective posterior rhizotomy is one of the few surgical procedures done under general anaesthesia with a very low mortality risk. All patients undergoing this procedure have shown a reduction in their muscle tone to varying extents and a concomitant improvement in their functional movements and gait. The change in spasticity is usually graded according to the modified Ashworth-Bohannon scale, which is summarised in Table 2.1 (Peacock & Staudt, 1991). Results showing reduction of spasticity conducted at various centres around the world have been graphically summarised in Figure 2.4.

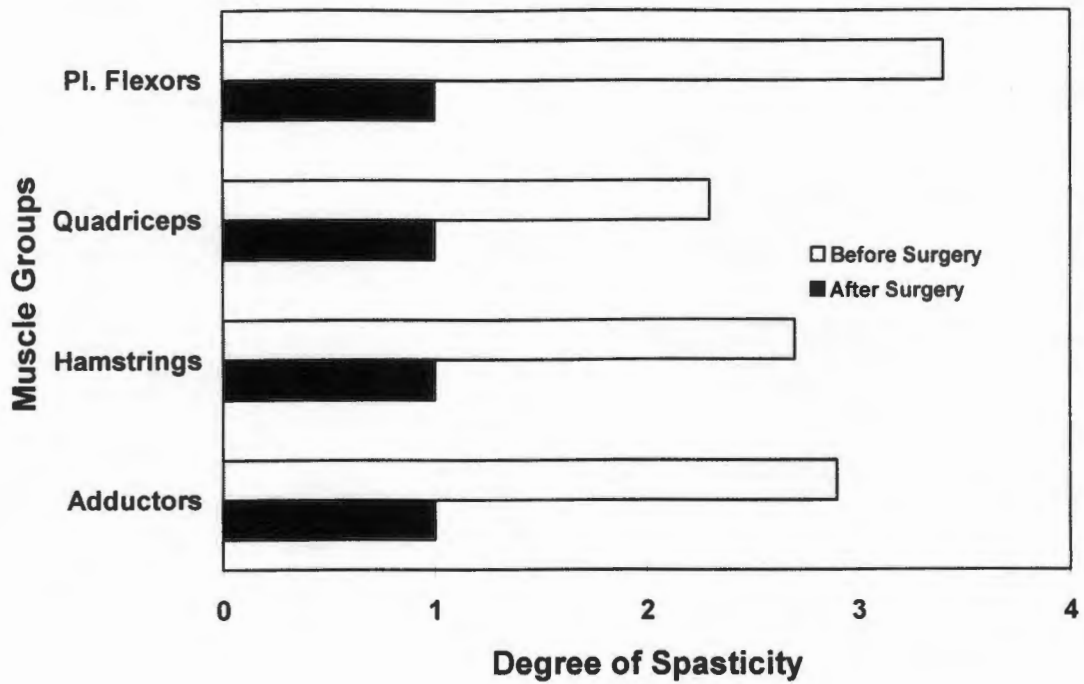
Figures 2.4 (a) and (b) indicate there is a definite shift towards decreased spasticity after surgery, implying that rhizotomy has an almost immediate effect in reducing increased muscle tone. An interesting finding by Lazareff *et al.* (1990) was that despite operating on a very small section of the lumbar area (only rootlets at the level of L4, L5 and S1 were subject to deafferentation), muscles not directly innervated by these segments — such as the hip flexors and some upper limb muscles (deltoid, biceps, and the

Score	Definition
0	Hypotonic: Floppy. Muscle tone less than normal.
1	Normal: No increase in muscle tone.
2	Mild: Slight increase in muscle tone. Minimal resistance to movement through less than half the range.
3	Moderate: Increase in muscle tone through most of the range of motion but affected part is easily moved.
4	Severe: Considerable increase in tone and passive movement difficult.

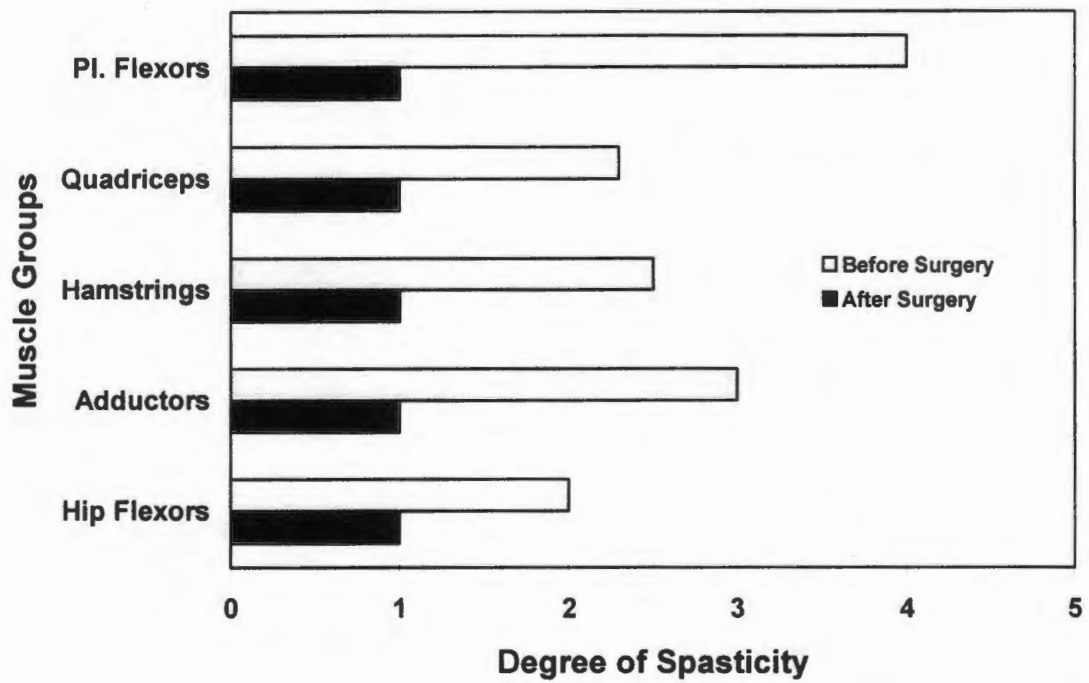
Table 2.1 Scale for grading spasticity [Ashworth (1964), Bohannon & Smith (1987)]

wrist flexors) — showed a reduction in spasticity. As can be seen from Figure 2.4 (c) and (d), there is a drastic reduction in spasticity in the muscle groups involved. In terms of functional improvements, this would mean a more normal posture when the patient is sitting or standing. Decreased spasticity in the adductors reduces scissoring of the legs displayed by children with cerebral palsy while the lowering of tone in the hamstrings and quadriceps reduces crouch gait, enabling the individual to adopt a more upright posture. Improvement of spasticity in the hip flexors can have mixed consequences. While the person may be able to stand more upright in due course, it may also reduce trunk control since some children use spasticity to compensate for lack of support from the anti-gravity muscles (Oppenheim *et al.*, 1991). Decreased spasticity in the plantar flexors results in reduction of equinus gait (Lazareff *et al.*, 1991).

The aspect of spasticity reduction most relevant to physiotherapists and occupational therapists is the improvement of functional capacities like sitting, standing, kneeling and walking. There have been a number of positive results published in this area

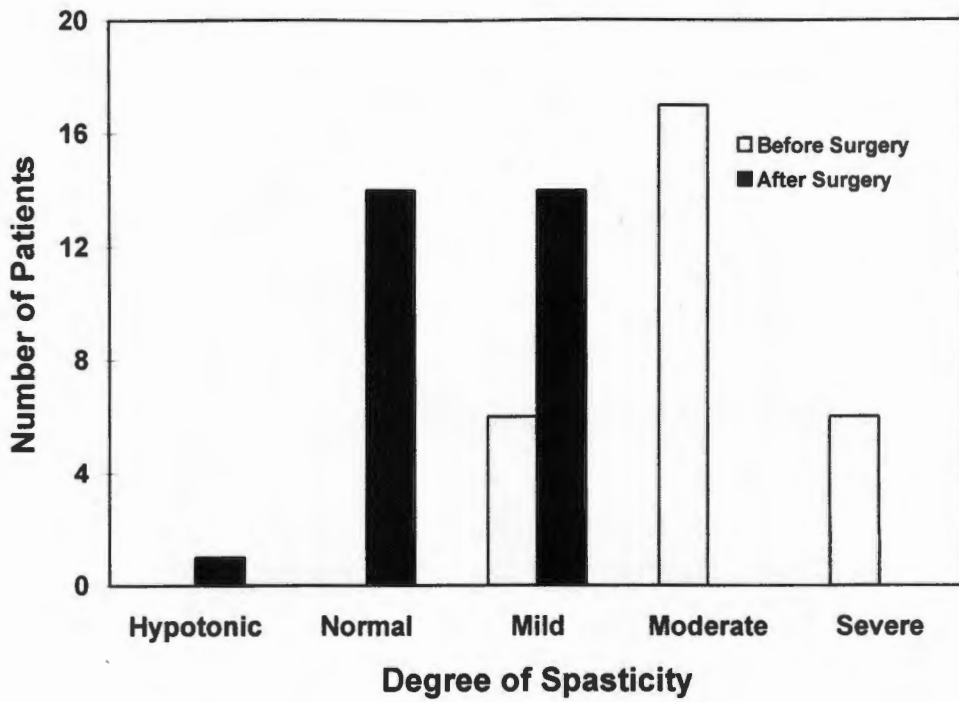


(a)

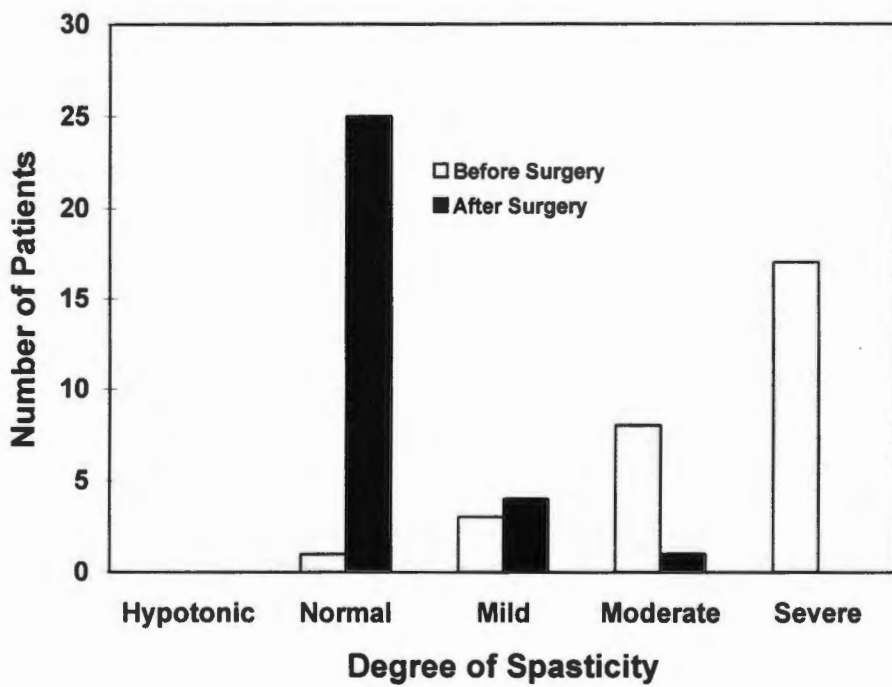


(b)

Figure 2.4 Degree of spasticity before and after surgery. (a) Peacock & Staudt (1991); (b) Abbott *et al.* (1993)



(c)



(d)

Figure 2.4 Degree of spasticity before and after surgery. (c) Berman (1987);
(d) Lazareff *et al.* (1990)

and these are tabulated in Table 2.2. The data listed includes only those patients classified as ambulatory. Post-operative evaluation in these cases was conducted in a time period ranging from 4 months to 10 years after surgery and not all patients were evaluated for each of the tasks listed. In addition, some of these patients may have been studied more than once by the same group of authors. While the overall improvement of functional abilities, especially sitting, is noteworthy, it can be seen that some of these children may partially lose their ability to stand and walk. This can probably be attributed to loosening of the hip flexors where the children had learned to use their spasticity to compensate for the weakness of the anti-gravity muscles. A very important aspect of the outcome evaluation of selective posterior rhizotomy is gait analysis of these children pre- and post-operatively. A detailed discussion regarding this is presented in Section 2.3.

2.2.5 Complications

Despite the fact that selective posterior rhizotomy is deemed to be a very successful neurosurgical procedure, various complications may occur as a result of essential secondary procedures performed at the same time. The most notable of these is spinal abnormality brought about by the laminectomy performed in order to proceed with the selective posterior rhizotomy. Peter *et al.* (1990) examined 55 children who underwent selective posterior rhizotomy and found that spinal abnormalities were present in 23 patients. An extensive 10 year follow-up study on 163 children revealed that 20% developed spondylolysis or spondylolisthesis (Peter *et al.*, 1993). Residual spasticity after selective posterior rhizotomy has been reported in a study conducted at the New York University Medical Center. Though this particular finding may be partly attributed to some roots with

Study	No. of Subjects	Sitting			Standing			Walking			Crawling		
		+	NC	-	+	NC	-	+	NC	-	+	NC	-
Peacock & Arens (1982)	7	83%	17%	0%	71%	14%	14%	100%	0%	0%	60%	40%	0%
Peacock <i>et al.</i> (1987)	40	98%	2%	0%	88%	8%	3%	87%	8%	3%	98%	2%	0%
Berman <i>et al.</i> (1990)	29	66%	34%	0%	52%	48%	0%	52%	48%	0%	41%	59%	0%
Peacock & Staudt (1991)	16	100%	0%	0%	88%	0%	12%	100%	0%	0%	66%	0%	33%
Peter & Arens (1993)	110	79%	21%	0%	72%	26%	2%	88%	11%	1%	Not tested		
Peter & Arens (1994)	30	70%	30%	0%	57%	40%	3%	86%	0%	0%	Not tested		

+ : Better

NC: No change

- : Worse

Table 2.2 The percentage of patients who experienced functional improvement after selective posterior rhizotomy
(Note: Not all patients were evaluated for each of the different activities)

abnormal responses being left intact, the exact reason for this is not yet known (Morota *et al.*, 1995). Other complications not directly related to the procedure itself include bronchospasms, pneumonia, bladder and bowel dysfunction, post-operative pain and sensory alteration. These complications, though minimal, can be avoided by identifying candidates who are at risk and administering suitable remedies (Abbott, 1992).

2.3 GAIT ANALYSIS

2.3.1 Normal gait

Human gait can be divided descriptively into two phases, stance and swing. The stance phase commences with heel strike and ends at toe off which marks the beginning of the swing phase at approximately 60 % of the gait cycle. Opposite toe off and heel strike occur at 10 and 50% of the cycle respectively (Gage, 1989). The stance phase can be further sub-divided into 3 periods: (1) initial double limb support or loading response; (2) single limb support or mid-stance; and (3) second double limb support consisting of the terminal stance and preswing. The swing phase is divided into initial, mid-, and terminal swing. These periods are defined by their respective gait events as shown in Figure 2.5 (Vaughan *et al.*, 1992).

Parameters used to describe normal gait are: (1) stance phase stability; (2) swing phase clearance; (3) foot pre-position in terminal swing; (4) adequate step length; and (5) energy conservation (Gage, 1993). Pathological gait is characterised by the absence of one or more of these parameters.

Factors measured in normal and pathological gait analysis are velocity (m/s), stride length (m), cadence (steps/min), range of motion and mid-range values (degrees) of the knee and thigh. The spatial-temporal factors change with age due to maturation of the muscles and bones of the lower limb (Sutherland, 1994). Pre- and post-operative pathological values, when compared to those of normal subjects, yield information on improvement of the subject's gait pattern.

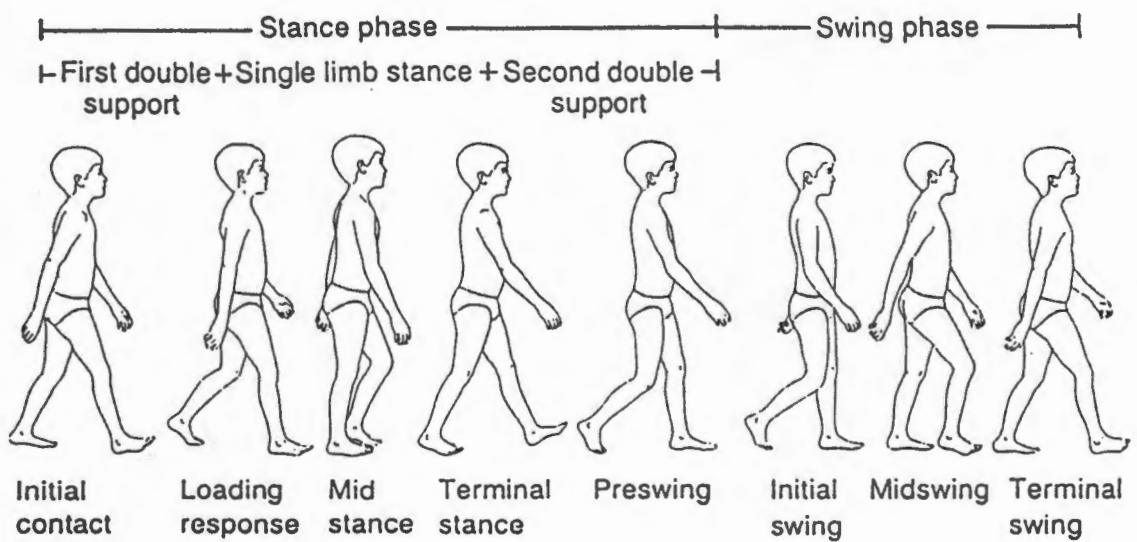


Figure 2.5 Gait cycle: events, periods and phases [Reprinted, by permission from C.L. Vaughan, B.L. Davis and J.C. O'Connor, 1992, *Dynamics of Human Gait*, (Champaign, IL: Human Kinetic Publishers)]

2.3.2 Pathological Gait in Cerebral Palsy

Cerebral palsy results in the following factors that affect gait: (1) loss of selective muscle control; (2) dependence of primitive reflex pattern for ambulation; (3) abnormal muscle tone; (4) relative imbalance between muscle agonists across joints; and (5) deficient equilibrium reaction (Gage, 1989). Manifestation of one or more of these conditions gives

rise to the pathological gait that is characteristic of cerebral palsy. A brief review of gait in cerebral palsy observed in the sagittal plane is given below.

At initial contact (0% of the cycle), the principal objective is to position the foot appropriately as it strikes the floor. This can be lost either through excessive flexion at the knee and/or excessive plantar flexion of the foot, resulting in a flat foot (if one of these abnormalities is present) or toe strike (if both abnormalities are present). During loading response (0 to 10% of the cycle), the body maintains smooth progression while decelerating the body mass. Weakness in the hip extensors and quadriceps muscles would produce an exaggerated flexion moment, requiring a posterior shift of the upper trunk to maintain stability. Mid-stance (10 to 30% of the cycle), marked by opposite toe-off, indicates the highest point of the body's centre of mass. There is an instability due to fixed flexion contractures of the iliopsoas and hamstrings. In the terminal stance and pre-swing phases (together consisting of 30 to 60% of the cycle), the triceps surae muscles (gastrocnemius and soleus) prevent extensive dorsiflexion of the ankle. Weakness in these muscles prevents heel rise and sustenance of knee extension, resulting in continued quadriceps action to maintain knee stability. This results in a slower walking velocity. Prevention of heel rise also results in the shortening of step length. In the initial and mid-swing phases (65 to 85 % of the cycle), insufficient hip and/or knee flexion produces inadequate foot clearance. Terminal swing (85 to 100% of the cycle) may be affected by overactive hamstrings or spastic quadriceps in the cerebral palsied child, resulting in partial knee extension which prevents heel strike (Gage, 1989).

2.3.3 Rhizotomy and Gait Analysis

Gait analysis is an important tool for measuring the benefits of selective posterior rhizotomy from a functional point of view, but relatively few results have been published in this area. A comparative review of three independent studies, by Vaughan *et al.* (1988), Cahon *et al.* (1990) and Boscarino *et al.* (1993), unanimously show improvement in stride length, velocity, knee and thigh range (Table 2.3), indicating a positive benefit of rhizotomy for these children. Although Boscarino and associates have presented their data in terms of the average leg length of these children, a clear improvement in the step and stride length is observed. These three studies involving age groups approximately spaced a year apart show a decrease in cadence in accordance with the findings of Sutherland (1984) although there was no significant post-operative change in two of the studies. This may be attributed to the fact that muscular weakness may not have resolved significantly in the short post-operative period considered in these studies. While all these results show a positive trend in the overall improvement of gait, factors such as the post-operative time interval and individual temperaments of individuals during the evaluation must be taken into account.

The only long term study of gait analysis so far published is that of Vaughan *et al.* (1991a) who conducted a three year follow-up study on the 14 patients evaluated earlier. Although cadence did not differ much in the later study, average speed and stride length showed a significant increase. A comparison between the two studies clearly shows a marked improvement in the range of motion at the knee and thigh, each tending towards the normal range of values (Figure 1.1 and 1.2).

Authors		Vaughan <i>et al.</i> (1988)	Cahan <i>et al.</i> (1990)	Boscarino <i>et al.</i> (1993)
No. of Patients		14	14	11
Post operative Period (months)		9	8.3	12
Median age (years)		7.7	6.5	5.5
Velocity (m/s) (* % Leg Length)	Before	0.67	0.62	1.4*
	After	0.79	0.77	1.4*
Cadence (steps/min)	Before	109	105	140
	After	105	106	124
Stride length (m) (* % Leg Length)	Before	0.72	0.68	1.26*
	After	0.87	0.88	1.39*
Knee range (degrees)	Before	39	Not Available	49
	After	50	Not Available	57
Thigh / hip range (degrees)	Before	39	Not Available	45
	After	53	Not Available	52

Table 2.3 One year post-operative gait analysis study on rhizotomy patients.

Another derived quantity was the thigh and knee mid-range point which can be used as a measure of the muscular control at a joint (Vaughan *et al.*, 1989). These values initially increased during the one year study and subsequently decreased, tending towards normal values, in the three year follow-up (Table 2.4).

	Cadence (steps/ min)	Stride length (m)	Average speed (m/s)	Knee Range (degrees)	Knee Mid-Pt. (degrees)	Thigh Range (degrees)	Thigh Mid-Pt. (degrees)
Pre-Op	109	0.72	0.67	39	40	39	15
1 yr	105	0.87	0.79	50	56	53	18
3 yr	103	1.03	0.90	56	44	51	13
Normal	115	0.90	0.85	61	35	42	6

Table 2.4 Comparison of gait parameters between a one year and three year follow-up study (Vaughan *et al.*, 1991a)

The aim of the proposed study is to perform gait analysis on the children last studied 7 years earlier by Vaughan *et al.* (1991a) to determine the long term effects (a post-operative period of ten years) of the surgery. As can be seen in Table 2.4, there is a definite improvement at three years after surgery in all the factors listed. The spatial-temporal quantities, however, change with age (Sutherland *et al.*, 1994) and it is crucial to determine how rhizotomy has affected development in these children, especially in the adolescent phase which is characterised by a growth spurt. Additional factors to be considered are the administration of physiotherapy and any subsequent orthopaedic procedures. This study endeavours to repeat the same tests conducted by Vaughan and associates in 1988 and seeks to establish the development pattern of the patients' gait ten years after the surgical procedure.

CHAPTER THREE

MATERIALS AND METHODOLOGY

This chapter provides a brief description of all the materials required and the methods employed in carrying out the various tasks included in the study. Prior to describing the techniques used to capture, process and analyse the data, it is crucial to lay down a set of hypotheses on which the foundation of the proposed study rests and this will be covered in section 3.1. Section 3.2 deals with the subjects who were selected and the criteria used, together with a brief history of each of the subjects along with brief information on the set of normals used for comparison. Section 3.3 includes the equipment, both hardware and software, the placement of the retro-reflective markers, and the technique for extracting and processing the data. The parameters to be evaluated are described in section 3.4 while section 3.5 deals with the data acquisition. The analysis of the data will be dealt with finally in section 3.6.

3.1 HYPOTHESES

To test the three hypotheses proposed in Chapter 1, it was essential to divide the entire set of available data from previous studies (Vaughan *et al.*, 1989; 1991a), the data from the current study, as well as data for normal age-matched subjects into five categories:

- A: Patients before surgery
- B: Patients one year after surgery
- C: Patients three years after surgery
- D: Patients ten years after surgery

E: Age-matched normal subjects

The validity of the hypotheses was tested by comparison between the above groups as follows,

Hypothesis 1 : A vs D

Hypothesis 2: C vs D

Hypothesis 3: E vs D

3.2 SUBJECTS

3.2.1 Selection Criteria

All subjects selected have cerebral palsy of congenital origin, the main criterion being the presence of spasticity. Selection for surgery was done by Dr. Warwick Peacock according to the following criteria (Berman, 1988):

1. Whether selective posterior rhizotomy would improve functional movement
(or facilitate caretaking in the case of quadriplegics)
2. Exhibition of spasticity
3. Absence of athetosis
4. Absence of underlying muscle weakness
5. Access to post-operative therapy

Criteria for selection for the present study has been solely on the basis of the fact that these subjects were part of two earlier follow-up studies (Vaughan *et al.*, 1989; 91a).

3.2.2 Patient History

The original study involved fourteen patients (eight male and six female) who were operated upon in 1985. Cerebral palsy in all these subjects was congenital. Their ages at the time of surgery ranged from two to fourteen years (mean age 8.2 years). All but one were diagnosed as diplegic. Of the fourteen, twelve were ambulatory in the community while two were classified as household ambulators. All but three had an IQ level of greater than or equal to 90 and were classified as educable. The IQ in the remaining three was between 50 to 90 and they were classified as trainable (Berman, 1988). Details about the subjects have been summarised in Table 3.1.

Of the original fourteen subjects, thirteen were located after a hiatus of seven years, while all possible attempts to track down subject 13 (JS) proved futile. Subject 9 (CS), although contacted, did not participate in the study as she left the country before commencement of data collection. It was not possible to gather gait data on subject 2 (JB) who, although he consented to participate in the study, underwent orthopaedic surgery to remove a growth on his foot just prior to the commencement of data collection. The subjects came from different races and socio-economic groups. The mean age of this group was 18 years 5 months at the time of evaluation. A questionnaire was sent to each of the subjects requesting permission and asking for relevant demographic information about the subjects. the questionnaire is presented in Appendix A.

3.2.3 Normal Controls

In order to test hypothesis three it was essential to obtain data from a set of age-matched normals. This was done by selecting twelve individuals between the

Patient	Initials	Sex	Date of Birth	Date of Surgery	Date of Study	Diagnosis	IQ
S1	AB	F	31.5.72	15.8.85	25.5.96	Q	>= 90
S2	JB	M	12.6.72	1985	*	D	>= 90
S3	AC	M	19.7.78	14.11.85	2.5.96	D	50 - 90
S4	SC	M	26.4.79	1.8.85	17.5.96	D	>= 90
S5	MJ	F	5.8.81	11.4.85	26.4.96	D	>= 90
S6	PL	M	19.1.73	2.5.85	16.5.96	D	50 - 90
S7	NM	F	10.12.82	31.10.85	3.5.96	D	>= 90
S8	BP	M	22.8.78	5.12.85	14.5.96	D	>= 90
S9	CR	F	n.a.	1985	**	D	>=90
S10	LR	F	10.1.77	3.10.85	13.5.96	D	>= 90
S11	FS	M	6.5.83	24.10.85	2.5.96	D	>= 90
S12	JS	M	n.a.	1985	**	D	50-90
S13	OW	M	16.3.76	13.6.85	24.4.96	D	>= 90
S14	MW	F	20.5.79	25.4.85	10.5.96	D	>= 90

Q: Quadriplegic D: Diplegic *: No data gathered; **: lost to follow-up; n.a: not available.

Table 3.1 Demographic data for patients who participated in the original study by Vaughan *et al.* (1988)

ages of fourteen to twenty two and requesting information about their height, weight, leg length (distance from greater trochanter to floor). the control subjects were also requested to give information about any neurological conditions that they may have and any orthopaedic procedures that they might have undergone. Details about the normal control subjects are presented in Table 3.2 These individuals were videotaped at the Medical Graphics unit at the Groote Schuur Hospital. The questionnaire filled in by these control subjects is presented in Appendix B.

3.3 EQUIPMENT

The schematic description of the process of data collection is as shown in Figure 3.1. The subject was asked to walk in a plane perpendicular to the camera lens. The recorded information was played back on a video cassette recorder (VCR) connected to a personal computer (PC) equipped with a frame grabber card. The frame grabber card was operated using a custom written software source code originally written for a three dimensional application by Ms. Barbara van Geems of the Biostereometrics group at the Department of Biomedical Engineering. This program was modified for a two dimensional gait analysis application and was called 2DGAIT.C. The output files from the program 2DGAIT.C were used as input files for the program CONVERT.PAS which converted the data from pixel coordinates to millimetres and also added information about the subject. This data file was then used in the program GAIT.PAS to display the data in various form as well as to plot the knee and thigh angles as a function of time. Details about the programs CONVERT.PAS and GAIT.PAS are given in Section 3.4.

Normal Control	Initials	Sex	Age	Height (cm)	Weight (kg)	Orthopaedic Procedures	Neurological Disorders
N1	AA	F	19	157	55	None	None
N2	AJ	F	20	160	52	None	None
N3	SB	M	22	170	60	None	None
N4	MG	M	18	172	59	None	None
N5	LK	F	21	157	49	None	None
N6	SK	M	21	172	57	None	None
N7	EL	F	22	162	71	None	None
N8	QL	F	19	157	56	None	None
N9	DR	M	21	180	77	None	None
N10	MT	M	19	172	75	None	None
N11	BV	F	16	172	59	None	None
N12	GV	M	14	155	50	None	None

Table 3.2 Demographic data obtained for the age-matched normal controls.

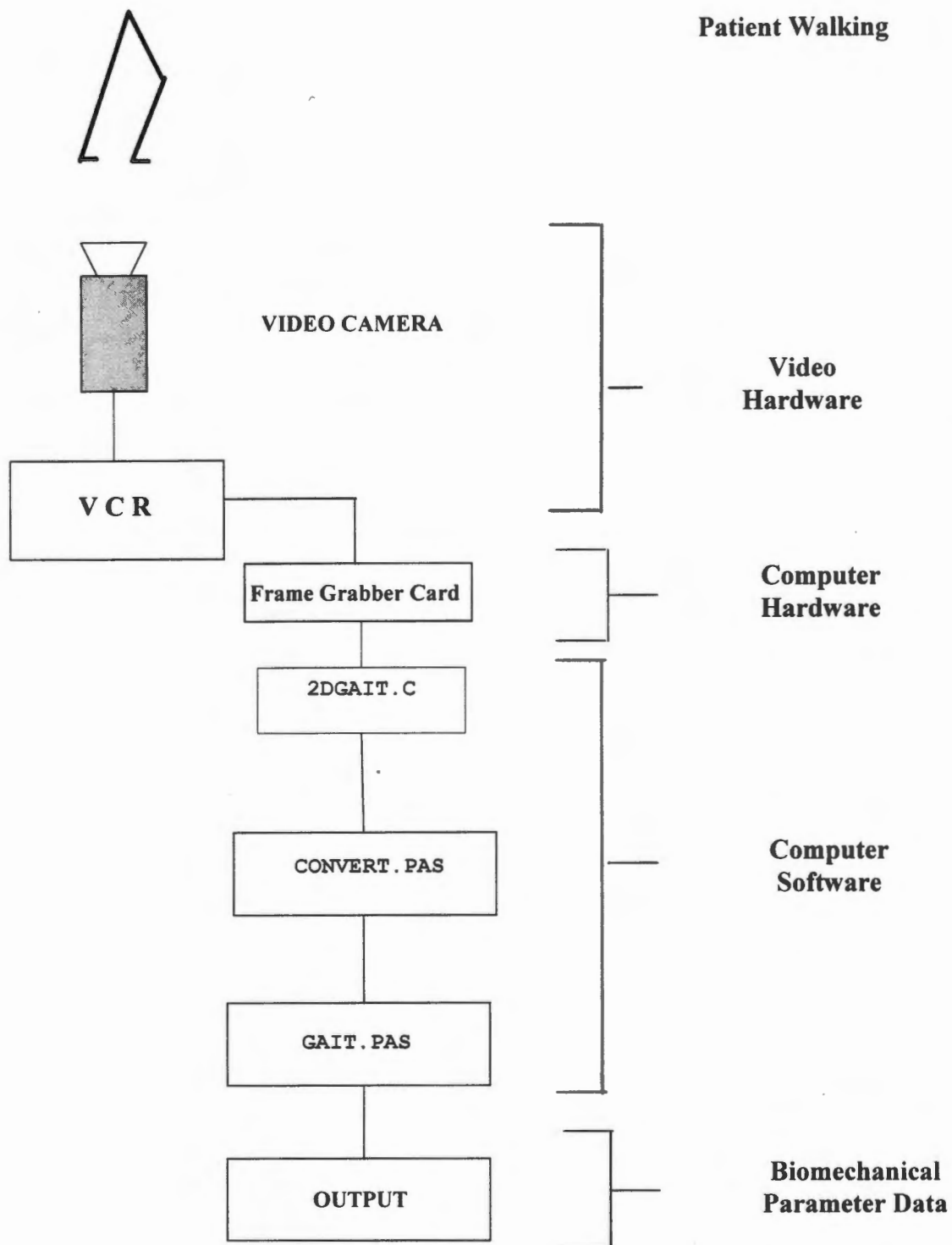


Figure 3.1 Schematic diagram of equipment used in the study.

3.3.1 Video Recording Systems

Data were gathered using three different systems. With the exception of two patients, all those residing in the Western Cape as well as the age- matched normals were videotaped at the medical graphics unit of the Grootte Schuur hospital using a VHS 1 recorder system (National Panasonic Corporation, Japan). The other two patients were taped using a surveillance camera unit (Burle Security Products Ltd., Cork, Ireland) housed in the Biostereometrics Laboratory in the Department of Biomedical Engineering. This, however, did not compromise the quality of the acquired data. The remaining patients residing around the country were videotaped using a National Panasonic camcorder belonging to the Department of Biomedical Engineering.

The method of data collection varied from the method employed in gathering data for the pre-operative as well as the one year and three year follow-up studies. The earlier system involved a digital camera system, the Microneye Motion Monitor (DigitEyes Inc., Clemson, SC), which registered the reflected light signals from the retro-reflective markers and directly fed the information into an IBM compatible PC which then analysed the data and plotted the required graphs. A comparison study between the two systems is presented in Appendix C.

3.3.2 Placement of Markers.

The markers used for the study were bottle caps (Yardley of London, Epping, Cape) covered with retro-reflective tape (3M Corporation, Minneapolis, USA). The diameter of these caps was 33 mm. A hole was drilled into the centre of each of these markers and a thick steel wire was inserted to facilitate the taping of the marker onto the subject. Three markers

were attached to each side of the subject with masking tape. The bony landmarks on which they were placed were the greater trochanter of the femur (to indicate the hip), the lateral femoral epicondyle (representing the knee), and the lateral malleolus of the fibula (representing the ankle) as depicted in Figure 3.2.

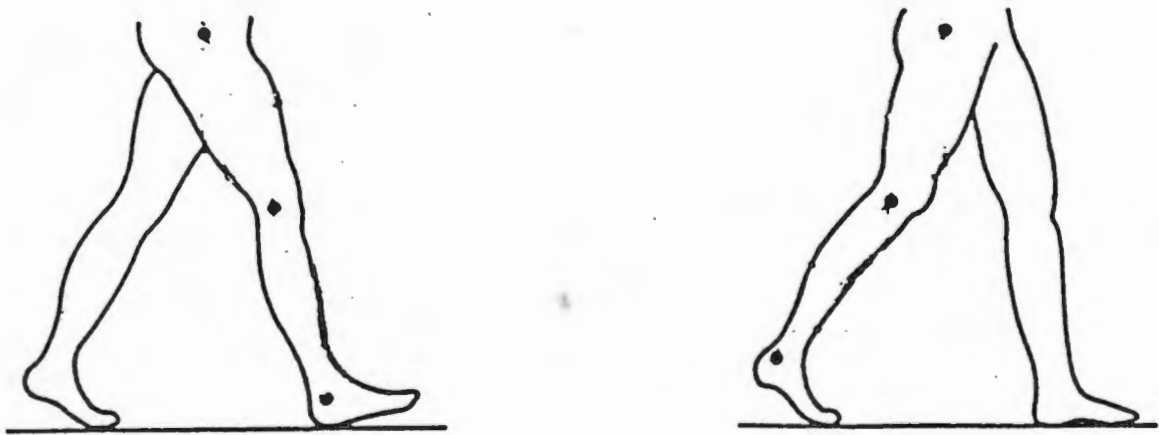


Figure 3.2 Placement of markers (Vaughan *et al.*, 1989)

3.3.3 Image Processing Card

The system used for data analysis was an IBM PC/486 equipped with an image processing card IP8/AT (Matrox Ltd, Quebec, Canada). The operation of the card required software source codes written in C and offered a wide range of capturing techniques, some of which were utilised in the processing of data for this study and are highlighted in the next section.

3.3.4 Software

Software was written for the study and incorporated a number of features such as data capture, digitisation, plotting the raw data in a variety of ways, calculating and plotting the knee and thigh angles, calculation of temporal data as well as the range of motion and mid-range values for the knee and thigh angles.

The source code to capture the raw video data was written in a combination of Turbo Pascal 5.5 and C ++ (Borland Int. Inc, Scots Valley, California, USA). The original source code was written in C ++ for a 3D application by Ms. Barbara van Geems and was modified significantly to adapt to the 2D system. This source code, 2DGAIT.C was responsible for setting parameters and adjusting the pixel level of the images to be digitised, snapping and digitising the control image (which marked the reference point with respect to which the markers on the subject was digitised), performing identical operations with the actual object, and storing the number of the marker positions in a file.

Modification of the C program involved setting the digitising card to read a single image instead of two and adjusting parameters to accommodate a faster shifting of frames to enable the analysis of gait. The main program also called upon executable programs written in turbo pascal 5.5 to convert data into a format readable by the programs responsible for the calculation of all relevant gait parameters. The turbo pascal programs originally written in version 3.0 for the earlier studies by Vaughan and O'Connor (Vaughan *et al.*, 1988) were converted into the 5.5 version. Making use of the basic algorithms and procedures written in the original software, two sets of source code were written for the purpose of analysis.

CONVERT.PAS read data generated from the digitising software and converted it into a form readable by the other program mentioned in the following paragraph. These text files could also be read into standard graphic software packages like Microsoft Excel and the data plotted. In addition to the X and Y co-ordinates in millimetres, it also includes personal data about the subject, scaling factors in the X and Y direction, and the exposure time (40 ms, given a frame rate of 25 frames per second for the video cassette recorder). The source code for the program is presented in appendix D

All relevant gait parameters were generated through a single program called GAIT.PAS which calculated the joint angles, plotted the raw data in a variety of ways as well as plotting the knee and thigh angles as a function of time and the knee angle as a function of the thigh angle. The program was also responsible for calculating all the relevant gait parameters like temporal data (cycle time, cadence, stride length and average velocity), the knee and thigh ranges of motion, their respective mid-range values, the area and perimeter of the region enclosed by the angle-angle diagram and the dimensionless ratio \sqrt{A}/P . In addition, it was also possible to obtain the knee and thigh angles written to a text file to facilitate reproduction of the various graphs with the help of commercially available graphics software packages. The details about these gait parameters are given in Section 3.4. The detailed source code for the software is presented in Appendix E.

3.3.5 Data Processing

Once the patient was video taped, the tape was played on a video cassette recorder and the program 2DGAIT.C was run. The camera parameters which set the pixel level, the level below which the pixels were not 'visible' to the digitising card was determined using the SET PARAMS function before the controls were snapped and digitised. The data file storing this

value was of the format *.TXT where * was the name given to that particular set of data. This text file was always called upon while digitising both the controls as well as the actual data. The controls were digitised using the control parameters option built into 2DGAIT.C. The controls were first “snapped” using the SNAP CONTROL function. The VCR machine was paused and the still image was set up for digitisation by the frame-grabbing card using the DIGITISE CONTROL function and the individual control points were then tracked using the mouse. Upon clicking the mouse, the X and Y co-ordinates in pixel units were written to a file with the characteristic extension *c1.TXT. The control files were manually modified by deleting the first line which indicated the number of markers and adding another line containing the actual values in millimetres of the horizontal and vertical distances measured during the recording session.

The tracking and digitisation of the object data were done using the AUTO TRACK function. This function called the file with the camera parameter information and also asked for the name under which the X and Y co-ordinates of the object (in pixel units) were to be stored. It then required careful movement of the tape frame-by-frame and digitisation of each of the markers that were being tracked by the digitising card. This method carried the risk of double digitisation which was remedied in the conversion program which automatically omitted points that were double digitised. The text files containing object data were saved under the filename of *1.TXT. The only modification done manually on the object files is the deletion of the first line indicating the number of columns. In some cases where the marker is “lost” due to obstruction or if the subject moved out of the range of the camera, these lines are also deleted.

The AUTO TRACK procedure was efficient in generating the X and Y co-ordinates for the data gathered in the confines of a studio, but did not work well for those sets of data that were gathered at the homes of subjects due to the presence of extraneous ambient light. Although all possible attempts were made in trying to eliminate this noise, such as minimising the lens aperture and darkening the light areas, an alternate technique had to be incorporated in the software to digitise the data. This method was incorporated into a function called SNAPPING MULTIPLE IMAGES and involved snapping and storing a series of images in sequential order for a particular set of data. The stored data were then recalled in the same order as they were stored and the markers were manually tracked and digitised using a mouse. The generated data was stored in a file with the characteristic extension *.ml.TXT. A major disadvantage of this technique was the enormous amount of memory required to store the images. A single image typically required about 44 Kbytes of memory and an average of sixty images was required to obtain a satisfactory set of data. This caused problems with the memory capacity of the hard drive in the PC used.

3.3.6 Software Output

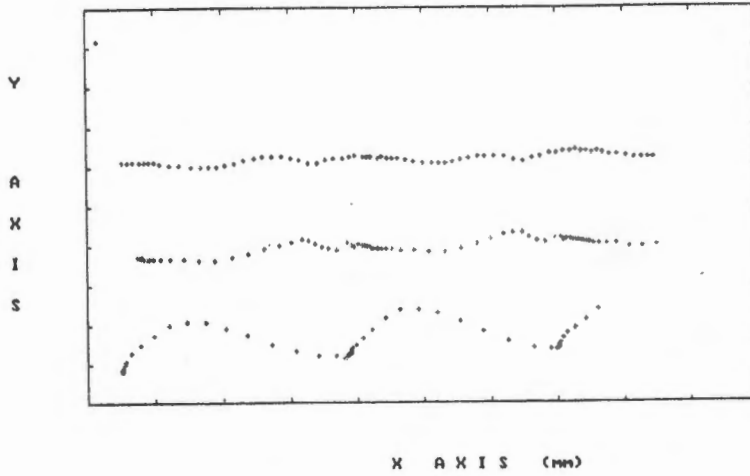
The program GAIT.PAS, apart from calculating the gait parameters, was also capable of graphically presenting the raw data in a variety of ways as well as drawing graphs of the knee and thigh angle as a function of time and the angle angle diagram. The diagrams included all relevant data regarding the subject.

The raw data could be graphically presented in one of three ways; (1) as raw data points, (2) as trajectories traced by the hip, knee and ankle markers and (3) as stick figures depicting the leg (Figure 3.3 a - c).

The knee and the thigh angles could be plotted only after the angles were calculated and the source code had a provision to ask the user if the calculation had been done. If the angles were not calculated, the software first completed the procedure before plotting the graphs. Figures 3.4 (a - c) depict the angular data for one subject (MJ), plotted by the software. A printout on paper could be obtained by pressing the print screen key after running the `graphics.com` command on the PC.

RAW DATA

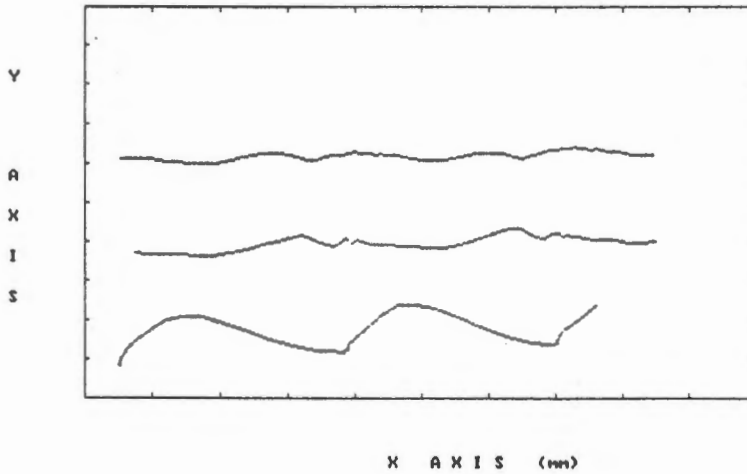
SUBJECT : MJ
DATE : 26.4.96
COMMENT : Female, 15 yrs, CP Right side walking.
FILENAME : nj4r.TXT
X Range : 3741.64 mm
Y Range : 1654.56 mm



(a)

TRAJECTORIES

SUBJECT : MJ
DATE : 26.4.96
COMMENT : Female, 15 yrs, CP Right side walking.
FILENAME : nj4r.TXT
X Range : 3741.64 mm
Y Range : 1654.56 mm



(b)

Figure 3.3 Data plotted as (a) Raw data points and (b) Trajectories of the hip, knee and ankle markers.

STICK FIGURES

SUBJECT : MJ
DATE : 26.4.96
COMMENT : Female, 15 yrs, Right side CP gait
FILENAME : mj4r.TXT
X Range : 3741.64 mm
Y Range : 1654.56 mm

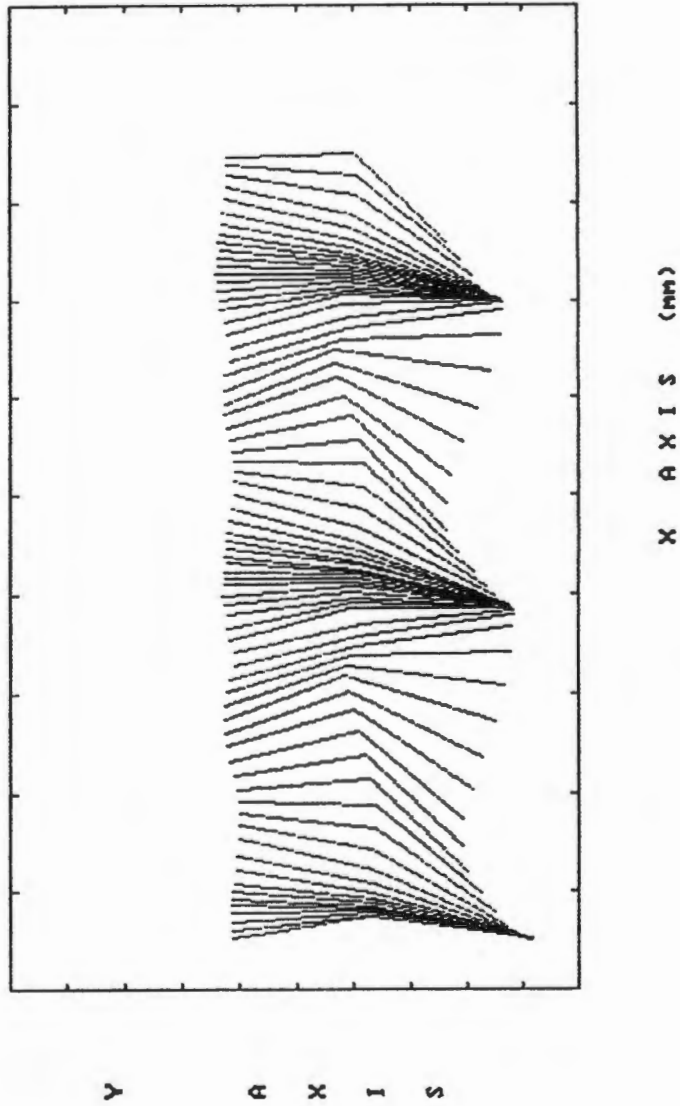
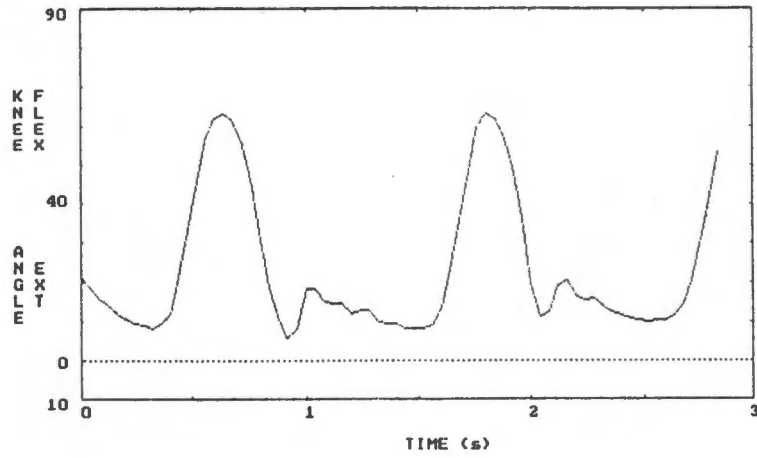


Figure 3.3 (c) Data plotted as stick figures.

KNEE ANGLE Vs. TIME

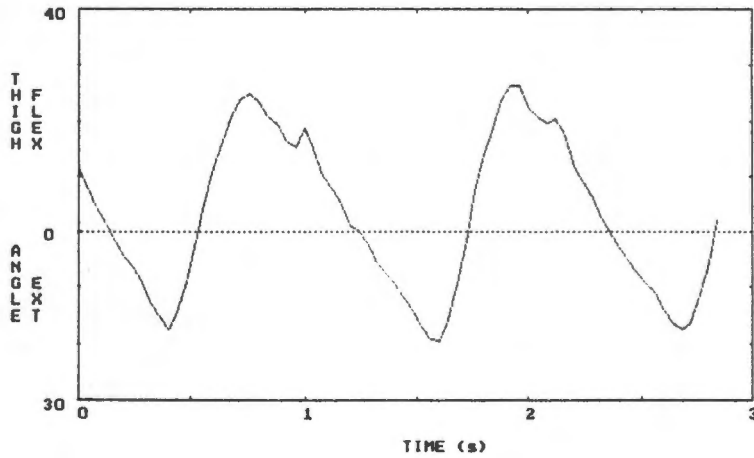
SUBJECT: MJ
DATE: 26.4.96
COMMENT: Female, 15 yrs, CP Right side walking.
FILENAME: nj4r.TXT



(a)

THIGH ANGLE Vs. TIME

SUBJECT: MJ
DATE: 26.4.96
COMMENT: Female, 15 yrs, CP Right side walking.
FILENAME: nj4r.TXT



(b)

Figure 3.4 (a) Knee angle vs time; (b) Thigh angle vs time

KNEE ANGLE VS. THIGH ANGLE

SUBJECT: MJ

DATE: 26.4.96

COMMENT: Female, 15 yrs, Right side CP gait

FILENAME: nj4r.TXT

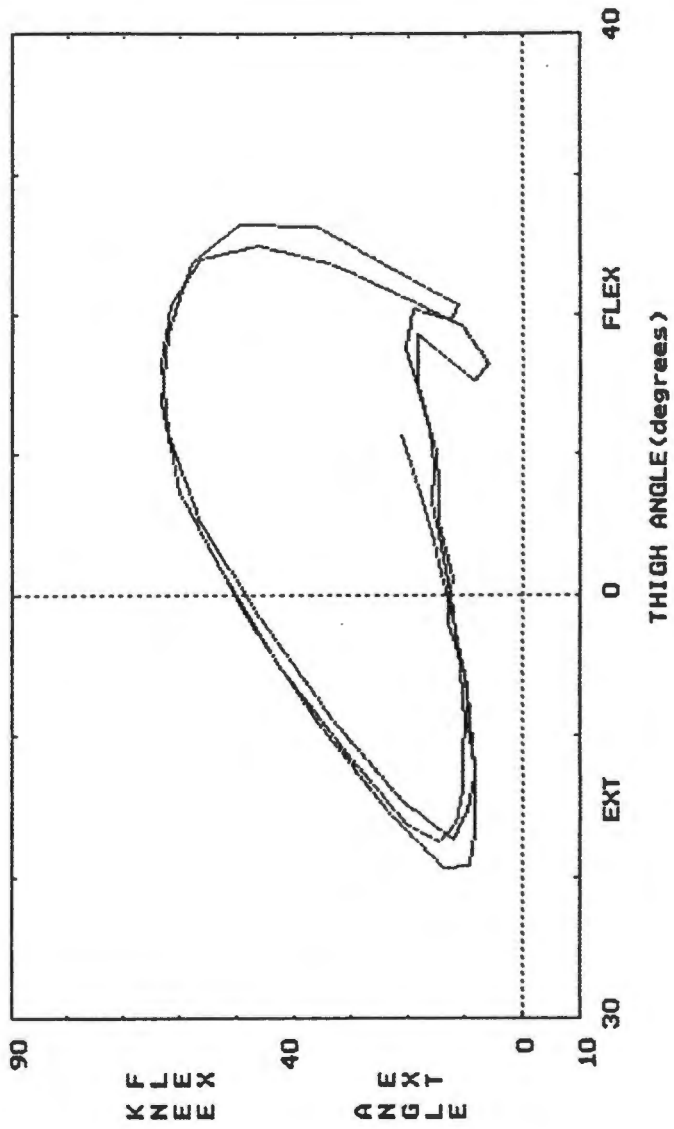


Figure 3.4 (c) Knee angle vs thigh angle.

3.4 GAIT PARAMETERS

The following section briefly discusses the gait parameters and their derivation from the acquired data.

3.4.1 Knee and Thigh Range of Motion

The evaluation of the knee and thigh ranges of motion is crucial to the analysis of gait since it is a direct measure of the active capabilities of the muscle groups involved in locomotion and hence a measure of the reduction in spasticity. The knee and thigh angles calculated by the software are as defined in Figure 3.5

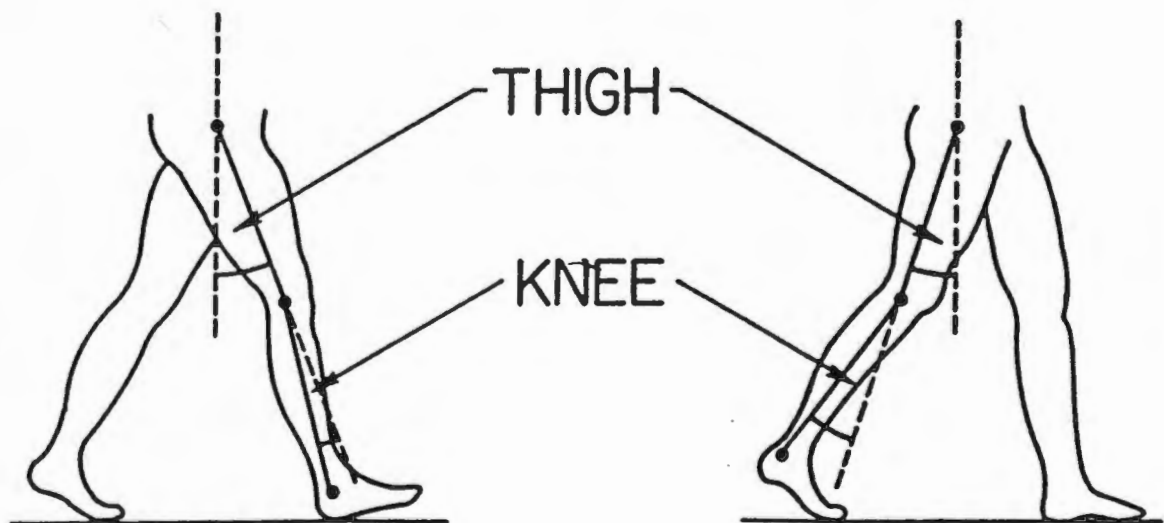


Figure 3.5 A sagittal plane view showing the positions of the markers over the hip, knee and ankle joints, and the definition of the knee and thigh angles (Vaughan *et al.*, 1989).

The first step is the calculation of the thigh length (distance between the hip and the knee markers) and the shank length (distance between the knee and the ankle markers) in terms of the X and Y co-ordinates in millimetres. The knee and thigh angles for each frame are calculated through the formulae shown below.

$$\theta_k(\text{frame}) = (\pm)\text{Tan}^{-1}\left(\frac{r_k}{\sqrt{(1-r_k^2)}}\right) \times \frac{180}{\pi} \quad (3.1)$$

$$r_k = \frac{\text{ShankX} \times \text{ThighY} - \text{ShankY} \times \text{ThighX}}{\text{ThighLength} \times \text{ShankLength}} \quad (3.2)$$

$$\theta_t(\text{frame}) = (\pm)\text{Tan}^{-1}\left(\frac{r_t}{\sqrt{(1-r_t^2)}}\right) \times \frac{180}{\pi} \quad (3.3)$$

$$r_t = \frac{\text{ThighX}}{\text{ThighLength}} \quad (3.4)$$

Where

- θ_k = Knee angle in degrees
- θ_t = Thigh angle in degrees
- ShankX, ShankY = Distance between the knee and ankle markers in the X and Y direction respectively (pixel co-ordinates).

ThighX = Distance between the hip and the knee markers
in the X direction (in pixel co-ordinates).

The range of motion is calculated as

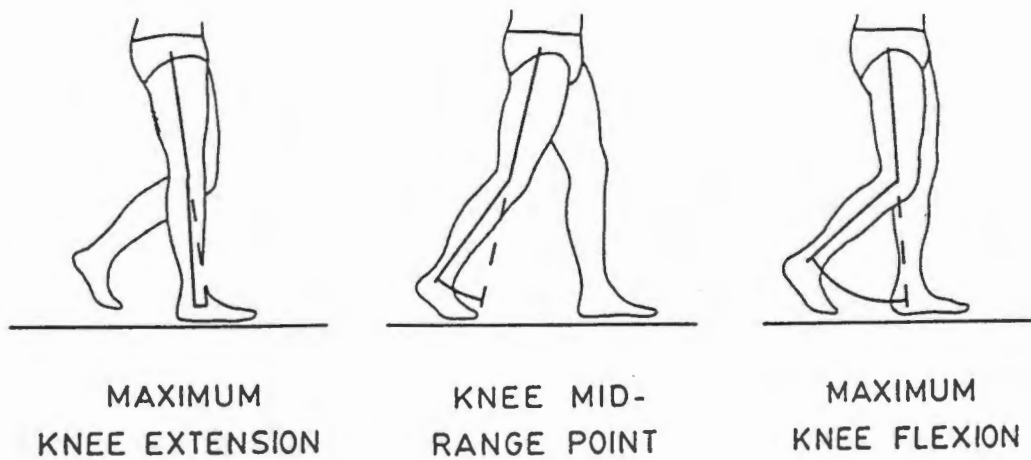
$$\text{Range of motion (ROM)} = \theta_I(\text{max}) - \theta_I(\text{min}) \quad (3.5)$$

where I= thigh or knee.

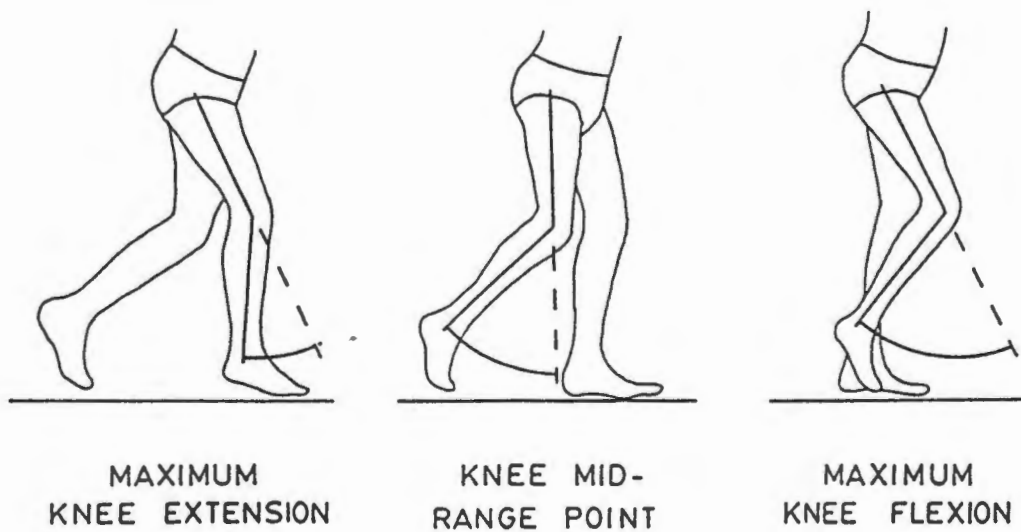
In cases of spastic gait, the range of motion may be considerably restricted due to co-contraction in the muscle groups acting across the hip and knee joints (Peacock & Staudt, 1991; Abbott *et al.*, 1993)

3.4.2 Knee and Thigh Mid-Range Point

The knee and thigh mid-range values are a measure of upright posture. The larger the value, the more “collapsed” the patient’s posture is during the gait cycle. In normal gait, these values occur at certain definite points during the normal cycle and tend to shift in the case of pathological gait due to muscular co-contractions and restrictions in range of movement (Vaughan *et al.*, 1991a). The degree to which these values shift towards the normal values is a useful criterion to determine the postural control that the subject exhibits during the gait cycle. The definition of the knee and thigh mid-range values for both the normal and pathological cases is shown in Figures 3.6 and 3.7 The program calculates the mid range values according to the following formula:

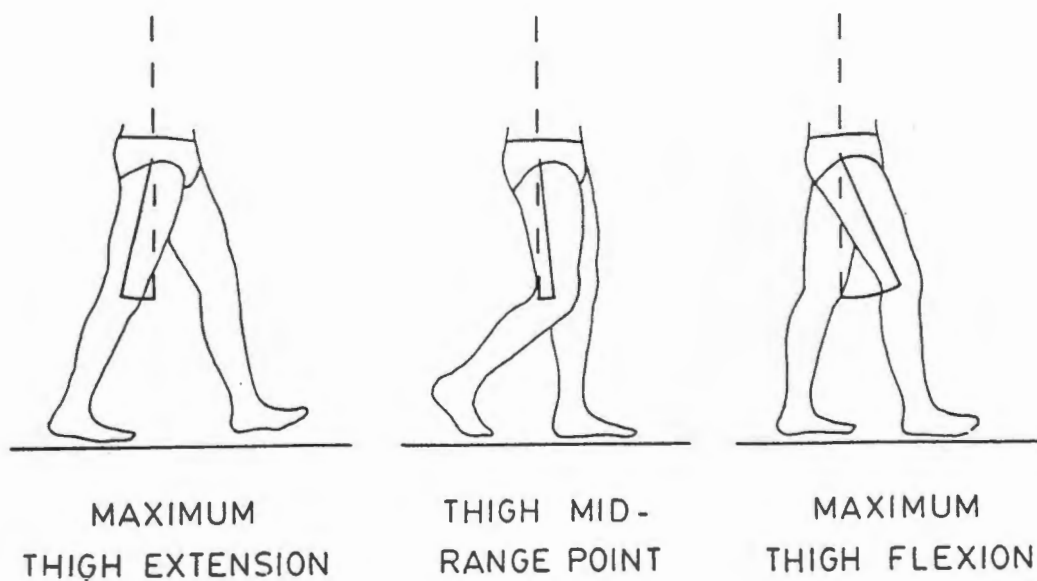


(a)

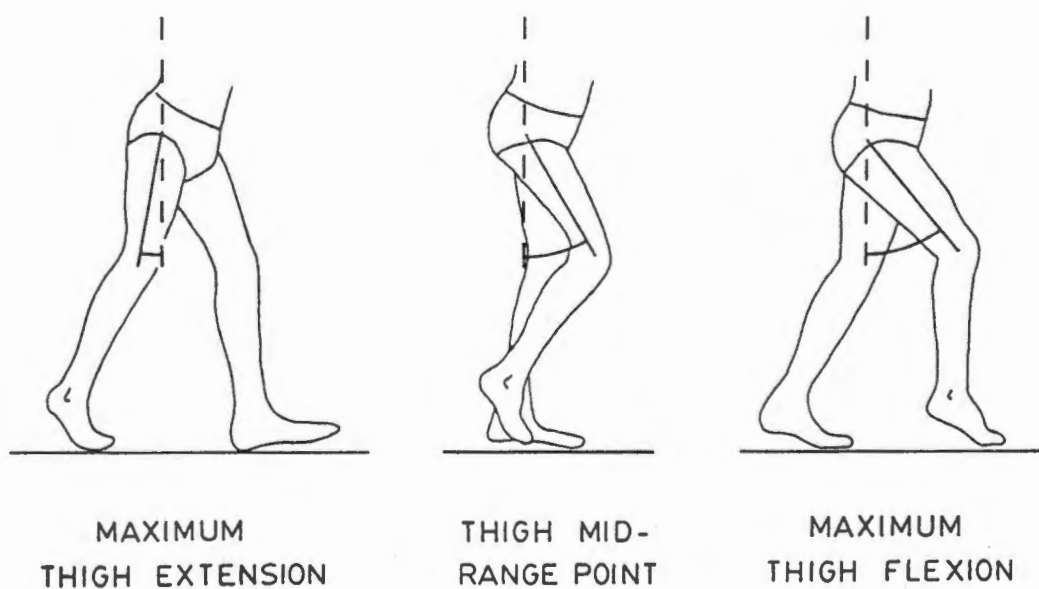


(b)

Figure 3.6 Definition of knee range of motion and mid-range point (a) in a normal adult and (b) in that of a spastic child (Vaughan *et al.*, 1991a)



(a)



(b)

Figure 3.7 Definition of thigh range of motion and mid-range point (a) in a normal adult and (b) in that of a spastic child (Vaughan *et al.*, 1991a)

$$\text{Mid-Range Point (MRP)} = \text{ROM}/2 + \theta_1 \text{ (min)} \quad (3.6)$$

where I = thigh or knee

3.4.3 Cycle Time

The cycle time is defined as the time required to complete one complete gait cycle. This factor is essential in calculating the temporal gait parameters, namely, average speed, cadence and velocity. The cycle time is calculated by determining the exact number of frames required for one gait cycle from the thigh angle vs time graph. The algorithm written for this parameter asks for the number of “turning points”, i.e. the number of times maximum and minimum value points appear on the graph (for the thigh angle there are approximately two turning points per cycle). This is then used to estimate the approximate cycle period. Using this factor, the exact number of frames and hence the cycle period can be calculated. The cycle time is then calculated as shown

$$\text{Cycle time} = \text{cycle period} * \text{Expose_time}/1000 \quad (3.7)$$

where the cycle period is expressed in terms of the number of frames and expose_time is the time taken for one frame (= 40 ms), the frequency of the VCR being 25 Hz. Details about the calculations of the frame rate is presented in Appendix F

3.4.4 Cadence

The cadence or the number of steps taken per minute is simply calculated as

$$\text{Cadence} = 120/\text{Cycle time} \quad (3.8)$$

3.4.5 Velocity and Stride Length

Velocity is defined by the equation given below:

$$\text{Velocity} = \text{Cadence} * \text{Stride Length} \quad (3.9)$$

The stride length, calculated by measuring the distance between two consecutive heel strikes on the same side of the body, is a measure of the knee and thigh ranges of motion while cadence is a measure of neural control, the rate at which the limbs are moved backward and forward. Velocity can be increased by increasing either of these independent parameters. The stride length and consequently the average velocity of movement is compromised in a person with cerebral palsy mainly due to the abnormal contractures of the muscle groups which hamper locomotion.

The program GAIT.PAS calculates this by measuring the X co-ordinates of the ankle marker at consecutive heelstrikes and multiplying this number by the X axis scaling factor taking into account the conversion factor into metres from millimetres,

$$\text{Stride Length} = [X_2(\text{ankle}) - X_1(\text{ankle})] * \text{ScaleX}/1000 \quad (3.10)$$

where the subscripts 1 and 2 represent the frames numbers at consecutive heel strikes. Dividing the stride length value by the cycle time (Equation. 3.7) yields the average velocity as defined by Equation 3.9.

3.4.6 Area and Perimeter

The software also plots the knee angle vs the thigh angle creating an angle-angle diagram. From this, the parameters of area enclosed by the angle-angle diagram (A) and

perimeter (P) and the dimensionless ratio \sqrt{A}/P can be calculated. The quantity A, being a function of both knee angle and thigh angle, is a direct measure of the total conjoint range of angular motion (the mapping of all possible ranges of angle-angle points during one cycle) experienced by the hip and knee joints during one complete gait cycle (Hershler and Milner, 1980). Figure 3.8 depicts a typical angle-angle diagram and the gait parameters that may be derived from it

Normal Male

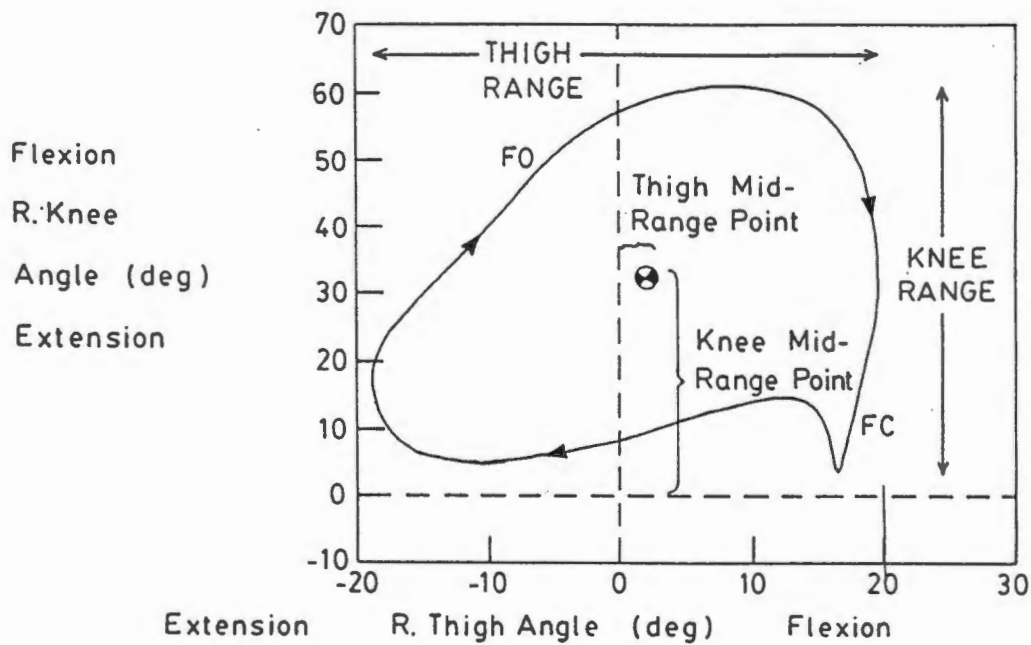


Figure 3.8: Angle-angle diagram for a normal male (Vaughan *et al.*, 1991a).

The area is calculated using a standard formula namely,

$$A = \frac{1}{2} \sum_{i=1}^{n-1} [(x(i) - x(i+1)) \times (y(i) + y(i+1))] \quad (3.11)$$

where;

A = Area enclosed by the angle-angle diagram

n = number of frames

$x(i)$ = thigh angle corresponding to the i^{th} frame

$y(i)$ = knee angle corresponding to the i^{th} frame

3.5 DATA ACQUISITION

Six retro-reflective markers were attached to the subject with masking tape, the positions being the greater trochanter and the lateral epicondyle of the femur, and the lateral malleolus of the fibula (Figure 3.2). The video camcorder was set at an average distance of about 3 metres from the plane of gait. The subject was required to walk in a straight line towards a fiducial marker placed at a known height from the floor. Having walked past the marker, the subject was required to turn back and walk along the same line away from the fiducial. For each recording, at least two stride length's worth of data for each leg was obtained.

Once the patient had been videotaped, two additional markers were placed in an "L" shape in the plane of gait. This was done to record the control points for calibration purposes. The actual vertical and horizontal distances as well as the distance between the camera and the plane of gait were measured with a steel tape and recorded. Temporal information regarding the speed was obtained by dropping a marker from a known height and digitising the images to determine the frame rate of the VHS recording system used. Details about the determination of the frame rate of the video system used are given in Appendix F.

3.6 DATA ANALYSIS

The gait parameters obtained upon digitisation and data processing were entered into a Microsoft Excel spreadsheet in order to facilitate comparison with the data obtained in the previous studies. This data could also be imported by STATISTICA (StatSoft. Inc., Tulsa,

OK, USA), a commercial statistical software package used for the statistical analysis of the data. A multiple analysis of variance (MANOVA) was performed on the data using time and side as the independent variables and the joint ranges of motion and mid-range values as the dependent variables. The level of confidence was set at the standard level, namely $p= 0.05$ or a 95% confidence level. A second set of data was used to obtain the statistical analysis of the temporal parameters in which the stride length, cadence and average velocity data obtained for both the 10 year study as well as the age matched normals were entered in terms of leg length. Post hoc comparisons were made using the Scheffé test (Winer, 1971). The results obtained from the tests are presented in the following chapter.

CHAPTER FOUR

RESULTS

This chapter presents the results of the gait analysis study conducted to determine the long term effects of selective posterior rhizotomy on the gait of individuals with spastic cerebral palsy. A summary of responses to the questionnaire sent out to the subjects (or, in the case of minors, to their parents) has been given in Table 4.1. The details include information about any orthopaedic procedures performed after the rhizotomy, physiotherapy received, the subjects' involvement in sports, capability in coping with daily household activities, and the subjects' overall outlook towards rhizotomy.

The biomechanical results are presented in the following order: ranges of motion and mid-range values for the knee and thigh; area and perimeter; and spatial-temporal parameters.

Following the biomechanical parameters, the results of the statistical analysis of the data are presented in terms of each one of the parameters investigated for the study.

4.1 SUMMARY OF RESPONSES TO QUESTIONNAIRE

A questionnaire mailed to each one of the subjects yielded information about how the individual benefited from the surgery. Responses indicated that all the patients except two (AB and PL) could cope normally with daily activities. Of the remaining two, one subject (AB), although quadriplegic, coped quite well with her wheelchair while subject (PL)

Subject	Date of Birth	Date of Surgery	Date of Study	Present Height (cm)	Orthopaedic procedures *	Physio-therapy *	Daily Activities	Academics	Sports	Outlook on Rhizotomy
AB	31.5.72	15.8.85	25.5.96	145	Yes	No	Copes well	Good	None	Mixed
AC	19.7.78	14.11.85	2.5.96	170	No	No	Copes well	Unsatisfactory	None	Positive
SC	26.4.79	1.8.85	17.5.96	164	Yes	Yes	Copes well	Good	Swimming	Positive
MJ	5.8.81	11.4.85	26.4.96	177	Yes	No	Copes well	Good	No interest	Positive
PL	19.1.73	2.5.85	16.5.96	164	Yes	No	No	Unknown	Swimming	Positive
NM	10.12.82	31.10.85	3.5.96	134	No	Yes	Copes well	Good	Cycling/ Tennis	Mixed
BP	22.8.78	5.12.85	14.5.96	178	Yes	Yes	Copes well	Good	Swimming	Positive
LR	10.1.77	31.10.85	13.5.96	152	Yes	No	Copes well	Good	Cycling/ Swimming*	Positive
FS	6.5.83	24.10.85	2.5.96	142	No	No	Copes well	Good	Cricket/ Chess	Positive
OW	16.3.75	13.6.85	24.4.96	171	No	No	Copes well	Good	Swimming	Positive
MW	20.5.79	25.4.85	10.5.96	158	No	Yes	Copes well	Good	School Sports/ Field Events	Positive

* : Orthopaedic procedures received after rhizotomy

* : Physiotherapy received at present

● : Competitive level

Table 4.1 Summary of questionnaire responses.

required special care, partly due to his mental handicap. All subjects except two (who were earlier diagnosed with IQ levels between 50 to 90) were coping very well with academics and a number of them are presently pursuing their tertiary education at Technikons around the country (AB, LR and OW).

Of the eleven subjects studied, six (AB, SC, MJ, PL, BP and LR) underwent some form of orthopaedic surgery after rhizotomy. Subjects AB, MJ and BP had foot surgery to straighten their toes while SC and PL underwent hamstring lengthening procedures. SC also had an Achilles tendon lengthening procedure performed, while LR underwent surgery to correct a misaligned spine that was affecting her gait. The extent to which these orthopaedic procedures might have influenced the ten year gait data will be examined in Chapter 5.

A noteworthy observation was the motivation of each subject towards sports. All but two (AB and AC) took part in some kind of sporting activity. Subject LR was involved in swimming at a competitive level while subject FS represented his school team in cricket and chess. Most subjects no longer received physiotherapy once they left school. One subject (NM) has shown signs of regression over the past two years due to reasons that are as yet unknown and is at presently using a crutch on her right side. Finally, all but two subjects (AB and NM) had a very positive outlook on rhizotomy. The mixed reaction of subject AB could be attributed to the fact that she was not an ideal candidate for rhizotomy and was advised against surgery (Berman, 1988). She consequently lost the ability to walk immediately after the surgery due to underlying weakness of the trunk muscles.

4.2 JOINT RANGES OF MOTION AND MID-RANGE VALUES

The average values of the knee and hip joint ranges of motion (abbreviated as KROM and TROM respectively) and mid-range values (abbreviated as KMRV and TMRV respectively) are given in Tables 4.2 to 4.5 while the data obtained for the age-matched normal control subjects is summarised in Table 4.6. These values represent the average for the left and right sides. It was decided to present the data in the aforesaid manner since statistical analysis of the data (described in more detail in Section 4.5) proved that there was no significant difference between the left and right sides. The separate left and right side data for the subjects have been presented in Appendix G while that for the normal controls is presented in Appendix H. These data for the normal controls compares well with those values published in the literature (Sutherland *et al.*, 1994)

In order to facilitate comparison, the values obtained pre-operatively, as well as those values obtained in the one and three year post-operative follow up, are also included. Columns pertaining to those subjects who could not be located for the three year evaluation, and who were therefore not available have been indicated by the abbreviation "n.a.". The mean value of the joint ranges of motion and mid-range values are presented graphically in Figures 4.1 to 4.4.

As can be seen from the above-mentioned diagrams, there is a slight decrease in the knee range of motion at ten years compared to the three year study. The mid-range values for the knee show that there is a slight decrease, tending towards the normal values. The hip joint range of motion graph clearly shows the ten year values to be close to normal values, indicating that there was a reduction in spasticity which was maintained over the years. The mid-range value, too, decreased considerably from the three year value and was not statistically different from the normal value.

Subject	Pre-Op	1 yr	3 yr	10 yr
AB	23	19	26	23
AC	26	38	70	51
SC	14	27	n.a.	42
MJ	68	59	60	56
PL	28	28	n.a.	50
NM	43	39	63	59
BP	46	84	63	58
LR	47	70	64	59
FS	65	75	67	55
OW	53	54	n.a.	60
MW	38	51	55	56
Average	41	50	59	52
S. D.	17	21	14	11

Table 4.2 Average knee range of motion values.

Subject	Pre-Op	1 yr	3 yr	10 yr
AB	50	58	60	22
AC	39	66	45	42
SC	74	68	n.a.	34
MJ	31	57	52	33
PL	31	74	n.a.	27
NM	35	51	34	50
BP	49	42	30	30
LR	31	49	31	42
FS	40	49	41	37
OW	39	41	n.a.	37
MW	42	65	60	46
Average	42	56	44	36
S. D.	13	11	12	9

Table 4.3 Average knee mid-range values.

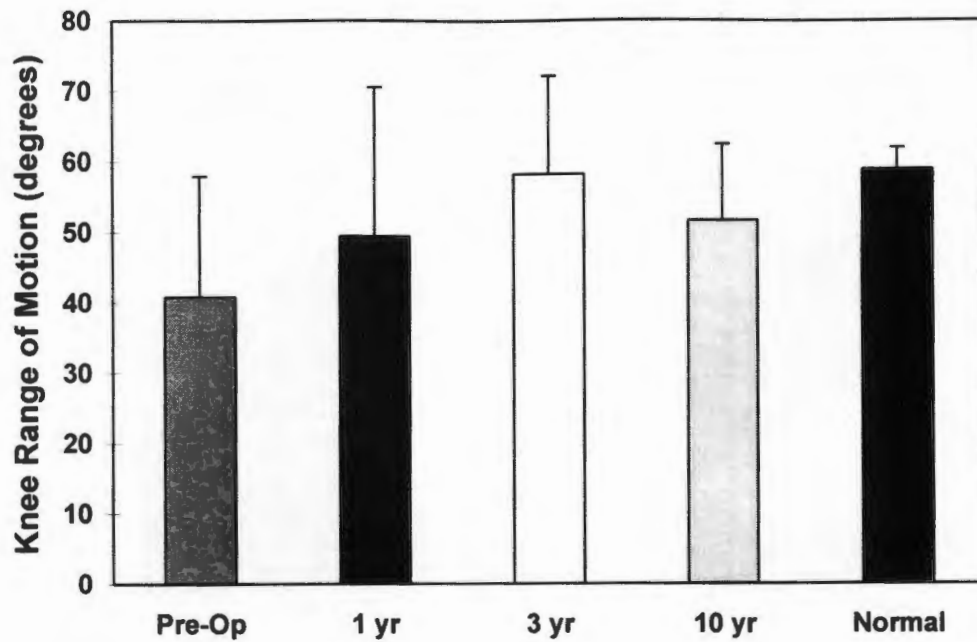


Figure 4.1 Variation in knee range of motion pre-operatively, one year, three years, ten years after surgery and average value for age-matched normals.

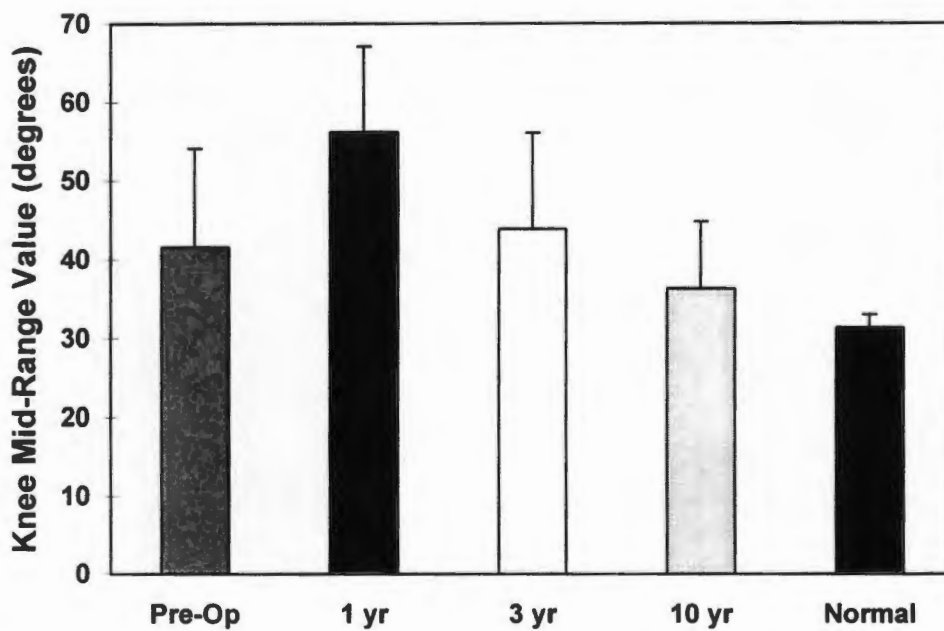


Figure 4.2 Variation in knee mid-range value pre-operatively, one year, three years, ten years after surgery and average value for age-matched normals.

Subject	Pre-Op	1 yr	3 yr	10 yr
AB	29	30	42	30
AC	35	60	63	40
SC	23	30	n.a.	38
MJ	59	55	46	46
PL	34	55	n.a.	35
NM	46	49	58	56
BP	47	70	50	53
LR	50	66	50	52
FS	38	64	53	49
OW	45	42	n.a.	42
MW	42	58	48	49
Average	41	53	51	45
S. D.	10	14	7	8

Table 4.4 Average thigh range of motion values.

Subject	Pre-Op	1 yr	3 yr	10 yr
AB	20	17	21	0
AC	12	20	18	15
SC	39	36	n.a.	13
MJ	3	20	16	3
PL	12	28	n.a.	6
NM	7	10	13	20
BP	18	13	6	3
LR	15	18	10	20
FS	11	13	8	5
OW	11	9	n.a.	6
MW	20	21	19	13
Average	15	18	14	9
S. D.	9	8	6	7

Table 4.5 Average thigh mid-range values.

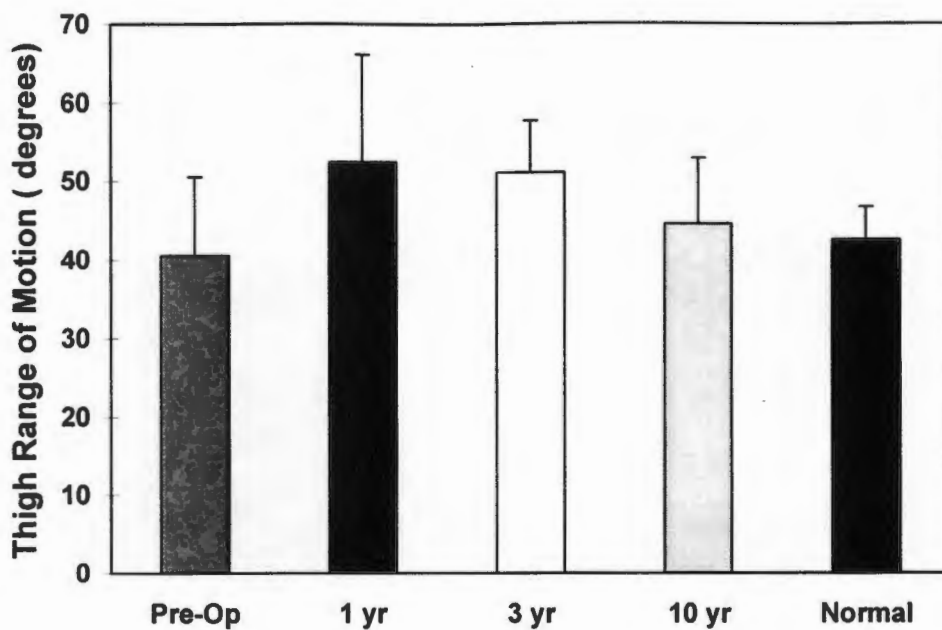


Figure 4.3 Variation in thigh range of motion pre-operatively, one year, three years, ten years after surgery and average value for age-matched normals.

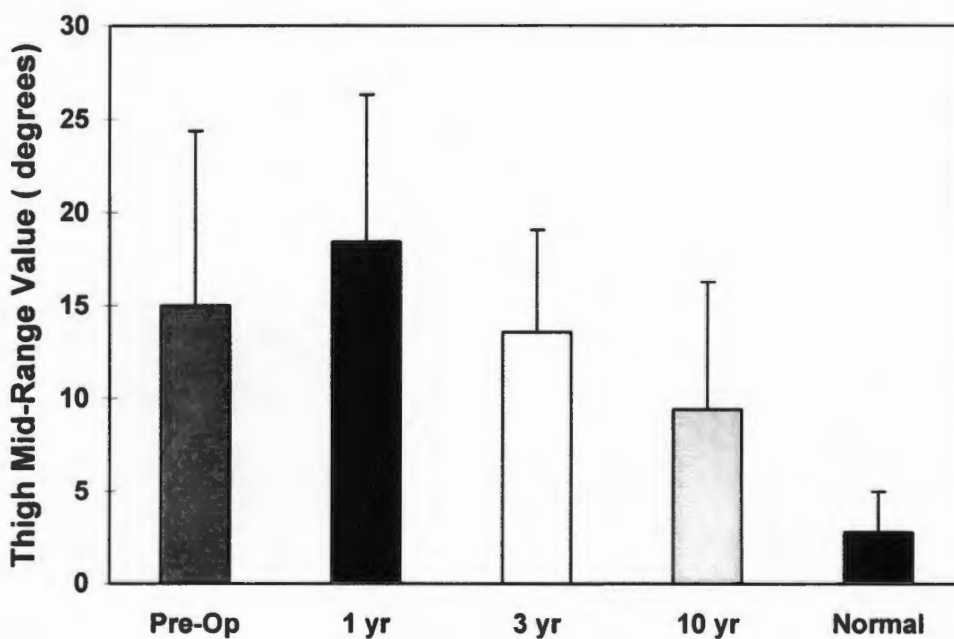


Figure 4.4 Variation in thigh mid-range value pre-operatively, one year, three years, ten years after surgery and average value for age-matched normals.

Normal Control	KROM	KMRV	TROM	TMRV
AA	63	32	50	3
AJ	61	36	43	3
SB	56	30	39	5
MG	59	31	40	2
LK	66	33	52	7
SK	56	32	43	5
EL	58	32	40	6
QL	60	30	44	2
DR	57	30	39	2
MT	60	30	41	-1
BV	56	31	40	1
GV	57	30	42	1
Average	59	31	43	3
S. D.	3	2	4	2

Table 4.6 Joint ranges of motion and mid-range values obtained for age-matched normal controls.

4.3 AREA, PERIMETER AND \sqrt{A}/P RATIO

The results obtained for the area enclosed by the angle-angle diagram and the perimeter as well as the \sqrt{A}/P ratio are presented in Tables 4.7 and 4.8. As with the previous section, the values obtained in the earlier studies are included for the sake of comparison. A statistical analysis of these parameters was not performed as they were just derived quantities from the joint ranges of motion and it would have yielded no extra significant information. As with the joint ranges of motion and mid-range values, detailed data about the left and right sides is given in Appendix G while the corresponding data for the normal controls is given in Appendix H.

AREA and PERIMETER										
Subject	Area (sq. degrees)					Perimeter (degrees)				
	Pre-Op	1 yr	3 yr	10 yr	Pre-Op	1 yr	3 yr	10 yr		
AB	382	273	447	244	90	90	157	91		
AC	466	988	1327	1014	108	86	191	139		
SC	187	383	n.a.	831	65	103	n.a.	138		
MJ	1732	1782	1139	1391	190	188	195	176		
PL	2843	768	n.a.	693	134	145	n.a.	142		
NM	462	935	2470	1050	148	153	283	186		
BP	902	2268	1174	1571	148	238	203	169		
LR	693	1666	1145	1155	159	205	191	152		
FS	1202	2162	1573	1332	173	241	234	163		
OW	1479	1374	n.a.	1326	155	159	n.a.	154		
MW	736	1592	714	1401	121	184	164	173		
Average	1008	1290	1248	1092	135	172	202	153		
S. D.	774	674	605	385	35	46	38	25		

Table 4.7 Values of area and perimeter obtained from the angle-angle diagram, pre-operatively and one year, three years and ten years after surgery.

$\sqrt{A/P}$ Ratio				
Subject	Pre-Op	1 yr	3 yr	10 yr
AB	0.22	0.18	0.13	0.14
AC	0.20	0.17	0.17	0.24
SC	0.21	0.20	n.a.	0.21
MJ	0.22	0.23	0.19	0.22
PL	0.20	0.19	n.a.	0.21
NM	0.15	0.21	0.16	0.19
BP	0.22	0.20	0.20	0.24
LR	0.17	0.21	0.18	0.23
FS	0.20	0.20	0.18	0.23
OW	0.25	0.23	n.a.	0.24
MW	0.23	0.22	0.20	0.22
Average	0.20	0.20	0.18	0.21
S. D.	0.03	0.02	0.02	0.03

Table 4.8 The $\sqrt{A/P}$ ratio values obtained pre-operatively and one year, three years and ten years after surgery

4.4 SPATIAL-TEMPORAL PARAMETERS

Spatial-temporal parameters such as cadence, stride length and average velocity were compared with those obtained from the age-matched set of normal individuals. For the sake of consistency, it was decided to present the parameters in terms of dimensionless units as recommended by Hof (1996). This required that the leg length (distance from the greater trochanter to the floor) be recorded. While this was measured directly for each of the age-matched normal controls, the value of leg length for the subjects was measured digitally from the videotapes and converted into metric co-ordinates using the scaling factor. The stride length was divided by the leg length while the average velocity v was converted in terms of the *Froude Number* $\sqrt{g/l_0}$ ($\bar{v} = v/\sqrt{gl_0}$). By normalising velocity in this way, it is possible to account for both the leg length and cadence changes that occur with increase in age (Hof, 1996). Cadence was converted into a dimensionless unit by first converting it in terms of hertz and then dividing each value by the term $\sqrt{g/l_0}$, as recommended by Hof (1996).

The original values obtained for the ten year study are presented in Table 4.9, along with the data obtained from previous studies for the sake of comparison. Table 4.10 depicts the dimensionless values obtained for the normals. Detailed left and right side values for the subjects and the normal controls are presented in Appendices G and H respectively.

TEMPORAL PARAMETERS														
Subject	CADENCE (steps/min)					STRIDE LENGTH (metres)					VELOCITY (m/s)			
	Pre-Op	1 yr	3 yr	10 yr		Pre-Op	1 yr	3 yr	10 yr		Pre-Op	1 yr	3 yr	10 yr
AB	61	47	29	37		0.71	0.41	0.78	0.41		0.36	0.16	0.19	0.13
AC	151	130	122	89		0.92	0.32	1.13	1.17		1.16	1.31	1.30	0.87
SC	83	87	n.a.	95		0.42	0.44	n.a.	0.83		0.29	0.32	n.a.	0.66
MJ	108	121	99	101		0.70	0.71	1.01	1.27		0.63	0.71	0.83	1.07
PL	84	92	n.a.	100		1.06	1.31	n.a.	0.78		0.72	1.00	n.a.	0.65
NM	40	55	55	57		0.31	0.38	1.08	0.88		0.10	0.17	0.49	0.42
BP	139	116	125	94		0.76	0.99	1.16	1.25		0.88	0.95	1.21	0.98
LR	134	110	119	93		0.59	0.89	1.04	0.68		0.64	0.81	1.04	0.52
FS	133	144	119	132		0.49	0.85	0.85	1.23		0.54	1.01	0.84	1.34
OW	125	117	n.a.	87		0.95	0.82	n.a.	1.08		0.99	0.81	n.a.	0.77
MW	101	120	129	108		0.72	0.81	1.03	1.25		0.58	0.81	1.11	1.13
Average	105	105	99	90		0.69	0.81	1.01	0.98		0.62	0.73	0.87	0.77
S. D.	35	30	37	25		0.23	0.32	0.13	0.29		0.31	0.37	0.38	0.35

Table 4.9 Value of spatial-temporal parameters (in standard units) obtained for the current study as well as previous studies.

Subject	Leg Length l_0 (m)	Froude No. $(\sqrt{g \cdot l_0})$	Stride Length (/Leg length)	Velocity (/Froude No.)	Cadence $(/\sqrt{g/l_0})$
AB	0.70	2.62	0.58	0.05	0.16
AC	0.89	2.95	1.31	0.29	0.45
SC	0.76	2.73	1.09	0.24	0.44
MJ	0.96	3.07	1.32	0.35	0.53
PL	0.84	2.87	0.93	0.23	0.49
NM	0.65	2.52	1.35	0.17	0.24
BP	0.86	2.90	1.47	0.34	0.46
LR	0.74	2.69	0.91	0.19	0.43
FS	0.80	2.80	1.54	0.48	0.63
OW	0.99	3.11	1.09	0.25	0.46
MW	0.79	2.78	1.58	0.40	0.51
Average	0.82	2.82	1.20	0.27	0.44
S. D.	0.10	0.18	0.31	0.12	0.13

Table 4.10 Leg lengths (in metres), the Froude number, and other spatial-temporal parameters obtained in dimensionless units for the ten-year study.

Normal Control	Leg Length l_0 (m)	Froude No. ($\sqrt{g \cdot l_0}$)	Stride Length (/Leg length)	Average Velocity (/Froude No.)	Cadence (/ $\sqrt{g/l_0}$)
AA	0.78	2.76	1.73	0.41	0.48
AJ	0.76	2.73	1.65	0.48	0.54
SB	0.88	2.94	1.78	0.57	0.64
MG	0.82	2.83	1.54	0.38	0.50
LK	0.78	2.76	1.55	0.39	0.50
SK	0.87	2.92	1.66	0.45	0.54
EL	0.76	2.73	1.53	0.42	0.55
QL	0.79	2.78	1.63	0.47	0.58
DR	0.87	2.92	1.40	0.39	0.56
MT	0.87	2.92	1.35	0.37	0.55
BV	0.86	2.90	1.37	0.41	0.60
GV	0.78	2.76	1.66	0.44	0.53
Average	0.82	2.83	1.57	0.43	0.55
S. D.	0.05	0.08	0.14	0.06	0.05

Table 4.11 Leg lengths (in metres), the Froude number, and other spatial-temporal parameters obtained for the age-matched normal controls.

4.5 STATISTICAL ANALYSIS

A factorial repeated measures analysis of variance (ANOVA) procedure was performed on the data to determine statistically significant differences at the $p < 0.05$ level of significance. The independent variables evaluated were time (at the pre-operative, one year, three year and ten year levels and also the values obtained for the age-matched normal controls, yielding a value of 4 for number of degrees of freedom), while the dependent measures were the joint ranges of motion and mid-range values. While time is not normally considered a “treatment” in the classical ANOVA models, it is appropriate for the repeated measures design considered here (Damiano *et al.*, 1995). In order to proceed with the

analysis, the missing data for three patients (SC, PL, OW) from the three year follow-up study were substituted with the average values of the gait parameters obtained from the remaining eight patients as suggested by the STATISTICA documentation. To complete a statistical analysis of the spatial-temporal parameters, the values of cadence, stride length, and average velocity in dimensionless units, were compared with those values obtained for the normal age-matched control subjects.

As can be seen from Tables 4.12, 4.14, 4.16 and 4.18, which depict the results of the multiple analysis of variance procedure (MANOVA) performed on the data, the results revealed no statistically significant differences between the left and right sides. However, there were statistically significant differences in joint ranges of motion and mid-range values across time.

Since significant differences were obtained for the joint ranges of motion and mid-range values, it was necessary to perform *post hoc* tests to determine the assessment time period within which the significant changes occurred. The test selected for this purpose was the Scheffé test and the results are given in Table 4.13 , 4.15, 4.17 and 4.19.

4.5.1 Knee Range of Motion

As can be seen from Table 4.12 indicating the effect of time and side on the knee range of motion, there is a significant difference between the pre-operative level and the three year level for the knee range of motion. This may be explained using Figure 4.1 and Table 4.13. As can be seen from the figure, the knee range of motion has increased to almost 60 degrees at the three year level and then decreased again, although the difference between the three year and ten year study is not statistically significant. This can be verified statistically from Table 4.13. The decrease in the mean value of the knee range of motion

may, to a certain extent, be attributed to the fact that one of the subjects (AB) was required to wear callipers which restricted movement of the knee on her right side, although the difference in the mean value when her datum is not included is only about 3 degrees. An important finding concerning the knee range of motion is that, upon taking the standard deviation into account, the knee range of motion value for the ten year data is essentially the same as the value obtained for the age-matched normal controls. In summary, the knee range of motion is seen to have increased significantly at the three year level and the range appears to have been maintained at ten years.

Effect	df effect	MS effect	F	p-value
Time	4*	1128.513*	4.946*	0.001*
Side	1	13.662	0.059	0.807
Time x Side	4	72.589	0.318	0.865

*: statistically significant, $p < 0.05$.

Table 4.12 Multivariate F tests for effect of time and side on the knee range of motion.

Time	Pre-Op	1 yr	3 yr	10 yr	Normal
Pre-Op	-	0.580	0.013*	0.315	0.006*
1 yr	0.580	-	0.444	0.993	0.337
3 yr	0.013*	0.444	-	0.720	0.999
10 yr	0.315	0.993	0.720	-	0.612
Normal	0.006*	0.337	0.999	0.612	-

*: statistically significant, $p < 0.05$.

Table 4.13 *Post hoc* Scheffé p values for the knee range of motion

4.5.2 Knee Mid-Range Value

As can be seen from Figure 4.2, the knee mid-range values seem to have consistently decreased after an initial increase at the one year post-operative level (Table 4.14). The *post hoc* comparison performed on the data revealed that there was no significant difference between the pre-operative data and ten year data. (Table 4.15) This was because the mid-range value, which increased significantly at the one year level, decreased at the three year level. This decrease continued at the ten year level, approaching the normal range of values. In fact there was no statistically significant difference between the values obtained at the ten year level and those obtained for age-matched normals.

Effect	df effect	MS effect	F	p-value
Time	4*	1989.480*	18.852*	0.000*
Side	1	1.821	0.017	0.896
Time x Side	4	0.082	0.103	0.981

*: statistically significant, $p < 0.05$.

Table 4.14 Multivariate F tests for effects of time and side on the knee mid-range value

Time	Pre-Op	1 yr	3 yr	10 yr	Normal
Pre-Op	-	4.7×10^{-4} *	0.963	0.577	0.030*
1 yr	4.7×10^{-4} *	-	5.9×10^{-3} *	1×10^{-6} *	0.000*
3 yr	0.963	5.9×10^{-3} *	-	0.199	0.0031*
10 yr	0.577	1×10^{-6} *	0.199	-	0.633
Normal	0.030*	0.000*	0.0031*	0.633	-

*: statistically significant, $p < 0.05$.

Table 4.15 *Post hoc* Scheffé p values for the knee mid-range value.

4.5.3 Thigh Range of Motion

A statistical analysis performed with the thigh range of motion as the dependent variable revealed a statistically significant difference in time (Table 4.16). Figure 4.3 shows that the thigh range of motion, which was close to normal values pre-operatively, increased by more than 10 degrees at the one year level. This was beyond the normal level, and was probably a direct result of increased freedom of movement due to the alleviation of spasticity. This initial increase was followed by a steady decrease in the range of motion over the next ten years in a such a way that, although there was a statistical difference at the three year level, there was no such difference seen at the ten year level. This is verified by the *post hoc* comparison presented in Table 4.17. Table 4.17 also reveals that there was no statistical difference between the range of motion at the year level and those of normals.

Effect	df effect	MS effect	F	p-value
Time	4*	617.68*	6.89*	5.9×10^{-5} *
Side	1	117.97	1.31	0.253
Time x Side	4	92.13	1.02	0.396

*: statistically significant, $p < 0.05$.

Table 4.16 Multivariate F tests for effect of time and side on the thigh range of motion.

Time	Pre-Op	1 yr	3 yr	10 yr	Normal
Pre-Op	-	0.002*	0.012*	0.738	0.971
1 yr	0.002*	-	0.992	0.110	0.016
3 yr	0.012*	0.992	-	0.279	0.062
10 yr	0.738	0.110	0.279	-	0.971
Normal	0.971	0.016	0.062	0.971	-

*: statistically significant, $p < 0.05$

Table 4.17 *Post hoc* Scheffé p values for the thigh range of motion.

4.5.4 Thigh Mid-Range Value

The MANOVA test performed on the dependent variable thigh mid-range value also revealed a statistically significant difference for time (Table 4.18). As can be seen from Figure 4.4, the thigh mid-range value increased after surgery and then decreased at the three year level. This decreasing trend continued at the ten year level such that there was a statistically significant difference between the pre-operative and the ten year level (Table 4.19). There was no statistically significant difference between the three year and ten year level, nor between the ten year values and those obtained for the age-matched normals. In summary, the thigh mid-range value can be seen to follow a decreasing trend towards normal values.

Effect	df effect	MS effect	F	p-value
Time	4*	827.73*	14.96*	0.000*
Side	1	184.47	3.33	0.070
Time x Side	4	24.33		0.779

*: statistically significant, $p < 0.05$

Table 4.18 Multivariate F tests for effect of time and side on the thigh mid-range value.

Time	Pre-Op	1 yr	3 yr	10 yr	Normal
Pre-Op	-	0.679	0.980	0.194	1.8×10^{-5} *
1 yr	0.679	-	0.325	0.0045*	0.000*
3 yr	0.980	0.325	-	0.499	2.3×10^{-4} *
10 yr	0.194	0.0045*	0.499	-	0.67
Normal	1.8×10^{-5} *	0.000*	2.3×10^{-4} *	0.67	-

*: statistically significant, $p < 0.05$

Table 4.19 *Post hoc* Scheffé p values for the thigh mid-range value.

4.5.5 Spatial-Temporal Parameters

In order to compare the temporal parameters obtained for the 11 subjects and those obtained for the set of 12 age-matched normals, it was necessary to convert the cadence, stride length and velocity to dimensionless numbers as presented in Tables 4.10 and 4.11 (Hof, 1996). The statistical analysis performed on the sets of data revealed that there was a significant difference between the values obtained in the ten year study and those obtained from the age-matched normals. Table 4.20 presents the p-values obtained for the comparisons of the temporal parameters.

Effect	df effect	MS effect	F	p-value
Cadence	1	0.1427	15.140	3.5×10^{-4} *
Stride Length	1	1.609	28.34	4×10^{-6} *
Velocity	1	0.294	34.44	1×10^{-6} *

*: statistically significant, $p < 0.05$

Table 4.20 Multivariate F tests for comparison of temporal parameters between the ten year study and those of age-matched normals.

4.6 SUMMARY OF RESULTS

Based on the results presented in the previous sections, and summarising them in the context of the initial hypotheses proposed, the following conclusions may be drawn:

(1) There was an increase in joint ranges of motion and a decrease in the joint mid-range values when comparing pre-operative data with the ten year data, but these changes were not statistically significant.

(2) Although the pre-operative and three year post-operative data were statistically different, there was no significant difference in the joint ranges of motion and mid-range values when three year data were compared to the ten year data.

(3) There was no significant difference between the CP subject data and data obtained from the age-matched normal controls with respect to the joint ranges of motion and mid-range values. There was, however, a significant difference in the spatial-temporal parameters with the CP subjects having lower stride length, cadence and velocity.

CHAPTER FIVE

DISCUSSION

The use of rhizotomy as a technique for the alleviation of spasticity first came into prominence in the late 1970's. Since then it has become one of the most frequently performed procedures in the world today for the alleviation of spasticity. The most important advantage of the alleviation of spasticity is the ability to acquire improved locomotor function and this involves an increase in the joint ranges of motion. So far there has been no long term objective gait analysis study which might clearly demonstrate the changes accrued in functional mobility after surgery, This is especially important in light of the fact that the subjects would have passed through the critical phase of adolescence. Another vital issue that needs to be discussed is the maintenance of the benefits gained by the subject over a long term in general and during the growth phase in particular. A third issue to be examined is the level to which the subjects' gait resembles that of normal controls in the same age group. Keeping these issues in mind, the three hypotheses proposed in Chapter 1 were formulated. Since a three year post-operative gait analysis study of subjects who underwent selective posterior rhizotomy yielded positive results (Vaughan *et al.*, 1991a), it was decided to extend the series of gait analysis evaluation to a longer term study.

Most of the subjects studied seven years previously were now in their teens or early adulthood and had already experienced or were passing through adolescence, a period normally characterised by a growth spurt and maturation of the entire body including the limbs. This made the need for conducting the ten year follow-up study all the more

important since to date, there has been no gait analysis study of such a long term period on any cohort of subjects who had undergone selective posterior rhizotomy in the last decade. This group of subjects was part of a prospective series of gait evaluations, and so each subject was used as his or her own control and it was possible to investigate improvements in gait parameters using previously obtained data for comparison.

The first section in this chapter is a discussion of the results presented in the previous chapter in terms of the hypotheses proposed in Chapter 1. This is followed by a brief discussion of the assumptions and limitations of the present study and the techniques used to overcome the limitations. In the third section, the results from the present study are compared with results obtained from previous long term subjective studies. Finally, the conclusions obtained from this study are presented in terms of the three hypotheses proposed.

5.1 HYPOTHESES

5.1.1 Hypothesis One

There will be a significant increase in range of motion at the hip and knee joints when ten year post-operative data are compared with pre-operative data.

Upon comparing the pre-operative data with the data obtained at the ten year study, it was seen that there was a difference between the two evaluations.

The change in the knee range of motion values, as can be seen from Figure 4.1 and Table 4.13, showed an increase after surgery at the one year follow-up study and this trend continued at the three year follow-up such that the difference was statistically significant.

This parameter, however, decreased slightly at the ten year study. Thus the difference between the pre-operative study and the ten year study was not statistically significant.

The knee mid-range value (Figure 4.2 and Table 4.15) increased significantly after surgery but decreased at the three year study. This decrease continued at the ten year level, approaching normal values, such that there was no significant difference between the pre-operative and ten year studies.

The functional significance of the increase in the knee range of motion is that the subject had a greater swing at the knee and hence the capability to cover a greater distance in a single stride. The decrease in the knee mid-range value, and hence a decrease in the flexion of the knee indicated that the subject exhibited less crouch in posture. This also meant that the subject could also be capable of achieving a better foot clearance during the swing phase hence assisting in the achievement of a heel-strike gait instead of a toe-strike at the commencement of the stance phase.

The thigh range of motion, which was almost equal to the normal range of values pre-operatively, increased beyond the normal range of values one year after surgery and the significant difference persisted at the three year level (Figure 4.3 and Table 4.17). This value decreased at the ten year study such that the pre-operative and the ten year values were not statistically different.

The pre-operative thigh mid-range value significantly exceeded the normal range of values and this increased further at the one year level (Figure 4.4). The value decreased at the three year level and continued to do so at the ten year level such that there was no significant difference between the pre-operative and ten year study (Table 4.19).

It was seen that immediately after rhizotomy, there was an increase in the thigh range of motion, which was close to normal values prior to surgery. This was accompanied by a sharp increase in the thigh mid-range value. This meant that the subject had acquired a larger range of motion but with a more flexed or crouched, rather than upright, posture. The thigh range of motion however, decreased at subsequent studies as did the thigh mid-range value with the result that the subject now had a more upright posture, due to the decrease in mid-range value in addition to a normal range of motion. This also indicated that the subject could walk without appearing to “stomp” during locomotion which is a characteristic of a high thigh mid-range value (indicating thigh flexion), thus enabling him/her to achieve a normal heel-strike gait.

Hence, although the first hypothesis could not be directly verified, the ten year data did not differ significantly from the improved values at three years.

5.1.2 Hypothesis Two

There will be no significant difference in joint ranges of motion when three and ten year post-operative data are compared.

The statistical analysis performed on the joint ranges of motion and mid-range value data clearly showed no significant difference between the three year and ten year post-operative data.

There was a slight decrease in the knee range of motion when the ten year data was compared to the three year data (Figure 4.1), such that the three year values were closer to normal values than the ten year data, but the difference was not statistically significant

(Table 4.13). The knee mid-range values showed a steady decrease, approaching normal values (Figure 4.2 and Table 4.15).

The absence of a significant change in the knee ranges of motion and mid-range values indicates that after an initial tendency of exaggerated swing at the one year study, the subjects exhibited a trend towards normal gait and this was maintained at the ten year level.

The thigh range of motion value obtained at the ten year study showed a trend similar to that of the knee mid-range value in that it too decreased slightly, compared to the three year level. The thigh range was slightly greater than but was approaching the normal range of values and there was no statistically significant difference (Figure 4.3 and Table 4.17). The thigh mid-range value also showed a decrease in value compared to the three year values, approaching the normal range (Figure 4.4 and Table 4.19).

This result was indicative of the fact that the increase in ranges of motion acquired by the subject appeared to be permanent and was maintained over a period of seven years between evaluations, despite the fact that this period marked the adolescent phase of most of the subjects and was characterised by a growth spurt.

Hence, hypothesis two is accepted.

5.1.3 Hypothesis Three

There will be no significant differences in joint ranges of motion and spatial-temporal parameters (cadence, stride length and velocity) when ten year post-operative data are compared with age-matched normals.

One of the most striking findings of this study was that there were no significant differences in the joint ranges of motion and mid-range values when these parameters were compared with data obtained from age-matched normals. This clearly indicated that in the long run, the subject is capable of achieving normal ranges of motion, suggesting that the decrease in muscle tone to normal levels may be permanent. This finding has very important consequences regarding the efficacy of rhizotomy as a permanent method for the alleviation of spasticity.

The knee range of motion registered a slight decrease compared to the three year value, but did not vary significantly from the normal range of values. In fact one of the most important findings was that the knee range of motion was essentially the same for the ten year data when compared to the normals (Figure 4.1 and Table 4.13).

As can be seen from Figure 4.2 and Table 4.15, the knee mid-range value, which increased after surgery, registered a decrease in value over the three year study and this trend continued at the ten year study such that there was no significant difference between the values obtained at the ten year study and those obtained from age-matched normal controls.

The fact that the knee range of motion and mid-range value did not differ significantly from the normal range of values is a clear indication that the swing phase of the gait cycle in these subjects closely resembles that of normal values. This suggests that the patients had a greater level of foot clearance during mid-swing and a less crouched posture.

Although the thigh range of motion exceeded the normal values at the one year post-operative evaluation (Figure 4.3), it was also marked by a similar increase in the mid-

range value; this finding indicated the “collapse” of the subjects’ posture as can be seen from Figure 4.4. The thigh range of motion decreased at the three year study and this continued at the ten year study and there was no statistically significant difference when compared to the data from the age-matched normals (Table 4.17). The mid-range value, however, decreased at a sharper rate after the one year study and maintained this trend at the ten year level such that the thigh mid-range value, like the other three parameters already discussed, did not differ significantly from the normal range of values (Table 4.19).

There was no significant difference in the thigh range of motion and mid-range values when comparing the post-rhizotomy subjects and the age-matched normal controls. This indicated that the subjects had acquired an upright position during the stance phase and were capable of standing erect in a normal fashion suggesting a higher level of hip control. This has important implications when one considers the long term advantages of the acquisition of an upright posture in terms of indirect complications like spinal deformities.

Upon performing a statistical comparison of the spatial-temporal parameters between the ten year post-operative data and the data obtained for the age-matched normal controls (Table 4.20), there was a significant difference between the two sets of data: the spatial-temporal parameters of the subjects were lower than normal values (Tables 4.10 and 4.11). It would however, be wise to interpret the spatial-temporal parameters with some caution. Velocity is a difficult quantity to control and may be influenced by factors such as mood or motivation. Referring to Equation 3.2, velocity is dependent on two factors, the stride length and cadence. The stride length in turn is dependent on the joint ranges of motion. Although the present study revealed no significant difference in joint ranges of

motion when compared to normal values, a factor to be taken into account is the fact that many of the subjects were studied in their homes which meant that space for locomotion was restricted. Cadence is dependent on neural control. In the cerebrally palsied individual, the motor cortex has been damaged before the individual has had the opportunity to “learn” the patterns of normal walking, which, in the normal individual, would be controlled by the extrapyramidal system after the initial learning procedure (Gage, 1991a). This means that the individual would have to depend upon the primitive reflexes to a certain extent, for the purpose of locomotion. Due to damage caused to the motor cortex which cannot be remedied, it may be speculated that the subject may not be capable of achieving the normal range of values in terms of cadence. Although the value of cadence was lower in the subjects, not only in the latest study, but in all the previous studies, it showed a decreasing trend according to the findings of Sutherland (Sutherland *et al.*, 1984). Hence, although the subject did not seem capable of acquiring normal walking speeds, their style of walking approached that of normal gait.

5.2 ASSUMPTIONS AND LIMITATIONS

In the case of ambulators, one of the primary goals of rhizotomy is to improve the quality of their gait. So far every published result on rhizotomy has confirmed this outcome. What, therefore, makes this particular study different from others? The answer is that this is the latest study in the first ever series of gait analysis studies conducted on the same cohort of patients who underwent rhizotomy a decade ago. When interpreting the findings, it is appropriate to realise there are a number of factors that may have had an influence on the results. These factors may be related to the subjects, or to an artefact of the

system used to conduct this study. The assumptions and limitations of the factors will therefore be explored in more detail.

According to Arens *et al.* (1989), a favourable outcome is most likely to occur in a younger age group, partly due to the expected improvement in the motor development, a view endorsed by Steinbok *et al.* (1992). The present study included individuals between the ages of 13 and 24 who underwent rhizotomy when they were between the age range of three and 14. Studying the joint ranges of motion and mid-range values from the point of view of age, the trend described by the above-mentioned authors could be discerned in the ten year study. One exception to the “rule” was subject NM, who although one of the youngest participants in the study — she was 4 at the time of surgery — has suffered a regression over the past two years. This fact was reported by the subject’s mother in the questionnaire and this was corroborated by her teachers at school. The cause however is as yet unknown and it would be premature to attribute her regression to rhizotomy. On the other hand, there were older subjects who showed a greater improvement (BP), and this might be attributed to the extra physiotherapy that this subject continues to receive.

Of the 11 subjects studied, only three were receiving physiotherapy on a regular basis in 1996. A fourth (MW), although attending a special school for cerebral palsied children, and hence with access to physiotherapy, does not receive it regularly. Of the three receiving physiotherapy on a regular basis, one (NM) had suffered a regression over the last two years.

In a study of 34 subjects who underwent selective posterior rhizotomy at the University of Washington, Seattle, five children received less than half the required amount of physical therapy after returning to their home communities and three of these children

made little or no improvement in function despite a decrease in spasticity (McLaughlin *et al.*, 1994). This may suggest that functional improvement of patients undergoing rhizotomy is mainly due to the intensive physiotherapy received by the subjects. However, this was not the case with the set of 11 subjects evaluated in the present study as can be verified from the results discussed in the earlier sections. Although the importance of physiotherapy and occupational therapy in the early years following surgery has been emphasised in a number of studies (Irwin-Carruthers *et al.*, 1985; Peacock *et al.*, 1987; Berman, 1989; Peacock and Staudt, 1991), improvements in gait parameters were observed,— and maintained over the years — despite the fact that most of the subjects had no access to long-term physiotherapy and occupational therapy. Although it may be argued that a possible control group could have been age-matched patients who had not received rhizotomy, the heterogeneity of CP precludes the usefulness of such comparisons (Blasco, 1991).

Prior to the introduction of selective posterior rhizotomy as a method for the alleviation of spasticity, the most prevalent techniques in use were orthopaedic techniques such as hamstring lengthening to improve a crouch gait pattern, gastrocnemius-soleus lengthening to decrease ankle equinus, and iliopsoas release to reduce hip flexion (Root, 1991). When hamstring lengthening is performed in conjunction with a rectus femoris transfer, it helps to reduce excessive knee flexion in stance while maintaining flexion in swing, thereby increasing the range of motion particularly during the swing phase of gait (Gage, 1991). In the current set of subjects studied, five underwent some type of orthopaedic procedure after rhizotomy (Table 5.1). Most of these were fairly minor augmentative procedures such as correction of deformities. Although rhizotomy is primarily useful in lowering muscle tone, the imbalance in the joints caused by spasticity is

not completely alleviated. With the lowering of muscle tone, this imbalance may become more pronounced and can lead to deformities which may be corrected only by orthopaedic procedures (Jonathan Peter, personal communication).

Subject	Orthopaedic procedure
AB	Correction of toe deformities by tendon releases
SC	Hamstrings and Achilles tendon lengthening
MJ	Straightening of left foot by tarsal osteotomy
PL	Hamstring lengthening
BP	Release of flexor tendon of second toe on both feet

Table 5.1 List of subjects who underwent orthopaedic procedures after rhizotomy

Only two of the subjects underwent relatively major tendon lengthening procedures. This may be due to the fact that one of these subjects (PL) was over 12 years old at the time of the neurosurgery and probably had a well established pathological gait pattern which may not have been correctable by rhizotomy alone. The other subject (SC), who was six years old at the time of surgery, was not an independent ambulator prior to surgery; he made use of a walker for locomotion and this may have impaired normal development of the lower limb muscles.

It seems unlikely that the orthopaedic procedures had an important influence on the results since equal levels of improvement were observed in patients who did not undergo orthopaedic procedures after rhizotomy. It may therefore be reasonably concluded that the

long term improvement of these subjects was primarily due to rhizotomy. However, it could be that on an individual basis, maximum functional benefit can be achieved by supplementing the rhizotomy with appropriate orthopaedic procedures.

An interesting aspect of the study was the influence of sports. All but three patients were involved in some type of sporting activity. Of the three who were not involved, one (AB) was quadriplegic, while subject AC was more interested in indoor video games. The third subject MJ, being shy by nature, was not very interested in sports. All the other subjects had obviously taken good advantage of the alleviation of their spasticity and were well motivated towards sport. The initial increase in the joint ranges of motion made possible by rhizotomy could have facilitated the participation in sports which in turn could have been a crucial factor in maintaining the increase in the range of motion. In fact, it may be argued that sporting activity contributed to an improvement in underlying muscle strength, thereby supplementing the post-operative physiotherapy.

The second set of factors that should be taken into account while interpreting the results is the reliability of the system used for obtaining the data. As has been mentioned earlier in Chapter 3, the method of data collection differed from the earlier studies in that a video recording system was used. In order to corroborate the validity of the data, a series of test studies were conducted using the two systems simultaneously, the results of which have been presented in Appendix C. As can be seen from these results, there was essentially no difference in the results obtained, indicating that the new method was equally successful in gathering data. The drawback of using the video system compared to using the digital camera was that in the latter, the gait parameters could be obtained almost instantaneously. This drawback was far outweighed by the fact that the video camera plus

VCR provided a permanent record of the subjects' progress. In addition, it was possible to extract the relevant data on a *post hoc* basis.

In the course of the post-operative follow-up study, four different video cameras were used to tape the subjects. In order to verify the uniformity of frame rate (which in turn affected the spatial-temporal parameters), a marker was dropped from a height of about 1.8m and the time taken for the marker to fall to the ground was calculated in terms of the number of frames. This test was performed for each of the cameras and all four sets of data yielded a frame rate of 25 frames per second. A sample study has been presented in Appendix F. This test ensured that the data obtained using different video cameras were temporally consistent.

One factor which may have affected the spatial-temporal values to a certain extent was the location of data collection. Some subjects (SC, PL, BP and LR) had to be studied in their own homes. Another subject from Cape Town (AC) was studied in the biostereometrics laboratory in the Department of Biomedical Engineering due to the non-availability of the Medical Graphics studio. This meant that there was a space restriction (the total walkway was only 4 to 5 metres long) such that it was possible to obtain only a little over 1.5 cycles worth of data. It is therefore questionable whether the subjects were able to attain their normal speed before they slowed down again. From Table 4.9 it can be observed that these four subjects did have a lower value of stride length and velocity. Subjective observation of their locomotion around their respective homes suggested that they might have been able to ambulate consistently faster if no restrictions had been placed on the walkway.

The software source code written for the analysis of the ten year study was a modified version of the source code written for the earlier studies (*cf.* Appendices D and E). While modifications were made to accommodate different versions of the editing and compiling software, no changes were made in the algorithms used to calculate gait parameters, thus ensuring that the processed values obtained were consistent with those obtained in the earlier studies.

5.3 COMPARISON OF RESULTS WITH LITERATURE

Rhizotomy has been performed on a regular basis in Cape Town since the early 1980s as a neurosurgical solution to alleviate spasticity. When combined with selective orthopaedic procedures and physiotherapy, the technique has proven itself to be a valuable technique in overcoming the disabling effects of spastic cerebral palsy. In the following paragraphs, the long term results and the benefits of rhizotomy found in the present study are compared and contrasted with other published findings.

The fact that the maximum benefits of rhizotomy may be reaped if the surgery is performed in early childhood, before extensive deterioration of motor function has set in, appears to be a unanimous verdict in all results presented. The earliest long term functional results to be published were those of the Italian group led by Fasano, whose patients were the first beneficiaries of this technique (Fasano and Broggi, 1989). In a report presenting results of functional outcome in 80 patients, only six were reported to have experienced some degree of return of spasticity. However, there was a lack of adequate post-operative physical therapy for these patients which may have resulted in a poor functional outcome. The present study found signs of regression in only one subject (NM) who, incidentally, had been receiving adequate physiotherapy. Fasano and Broggi (1989) also reported that

younger patients exhibited the greatest long term functional improvement, a fact that has been verified and confirmed in our study. Another finding that was observed in the Italian study was an improvement in finger dexterity, an observation noted in one of the subjects in the present study (LR).

In a long term report published by Arens *et al.* (1989), where 51 patients who underwent selective posterior rhizotomy between 1981 and 1984 were studied, 45 were still receiving physiotherapy. Of these, 42 were still making progress while three remained unchanged. Of the remaining six patients who did not receive physiotherapy, one (a mildly spastic, intelligent ten year old) was reported to have an improved gait pattern that bordered on normal within a year after surgery and this was being fully maintained five years after surgery. In the same study, only four of the ten independent walkers (prior to rhizotomy) could walk at least five minutes outdoors. At the long term follow-up, the total number of community walkers had increased from four to 15, and four others were fully independent indoors. Results from the present study agreed with the subjective findings of Arens *et al.* (1989) in that rhizotomy helped patients to improve their ambulatory capacity. All the subjects in this study were independent ambulators prior to surgery and were able to improve their gait significantly after their surgery (except subject AB) due to the increase in the joint ranges of motion and to maintain this gain. In addition, the initial increase in the joint mid-range values, indicative of a flexed or collapsed posture, was seen to approach the normal range of values (*cf.* Figures 4.2 and 4.4).

Peter and Arens (1993), in their report on the long term assessment of 110 patients who underwent rhizotomy in the 1980s reported that 97 of these patients had improved their patterns of ambulation although a formal gait analysis was not conducted. The present

study also observed an improvement in gait parameters, which are indicative of ambulatory patterns in an individual, in all the subjects studied (except in the case of AB for reasons explained in Chapter 4, Section 4.1).

The results presented in Chapter 4 clearly show that the results obtained from the cohort of subjects studied are consistent with results established in other long term studies. In addition, the subjects in the present investigation have not only maintained the improvements made possible by rhizotomy, but also seem to have progressed in such a way that their gait patterns (with respect to their joint ranges of motion and mid-range values) at present, match those of normal individuals of their age group. Their spatial-temporal parameters, however, do not match the age-matched normals.

It has been argued that the improved function that patients acquire after rhizotomy is not related to the reduction of spasticity by the procedure, but due to the intensive physiotherapy received (Steinbok *et al.*, 1992). The administration of physiotherapy immediately after the surgery is essential both to increase strength and to enable the patient to “unlearn” the pathological gait patterns acquired prior to surgery, thereby learning a new gait pattern. The younger the rhizotomy recipient, the faster it is to acquire a normal gait pattern. This study clearly shows that, in the long run, physiotherapy is an added advantage to the subjects, but benefits acquired by the procedure are maintained despite the non-availability of physiotherapy.

In a study conducted by Damiano *et al.* (1995), investigating the effects of quadriceps strengthening for the improvement of functional improvement and gait, it was observed that boosting muscle strength in these children appeared to produce an improvement in gait. This treatment however is highly selective and improvements vary

from individual to individual (Damiano *et al.*, 1995). Selective posterior rhizotomy, on the other hand, works by lowering the tone in muscles and facilitates easier movements of joints. One of the problems with rhizotomy is that it can unmask underlying muscle weakness (Berman *et al.*, 1990). One sequela of this weakness may be the increase in the mid-range values for the knee and thigh angles seen one year after surgery (Figures 4.2 and 4.4). It is therefore possible that the muscle strengthening regime advocated by Damiano *et al.* (1995) could be a very useful adjunct in the post-operative care of rhizotomy patients. In fact, muscle strengthening may even be a strategy worth pursuing prior to the rhizotomy procedure.

Peter *et al.* (1990) examined 55 children, operated seven years earlier for spinal abnormalities, and found that 23 children had developed mild scoliosis while five children had developed spondylolysis. In another study conducted by Peter *et al.* (1993), investigating the specific incidence of spondylolysis and spondylolisthesis after laminectomy, 99 out of 163 subjects were observed to have some involvement. This was attributed more to the result of increased physical activity of the subject after rhizotomy rather than side effects of the laminectomy itself (Peter *et al.*, 1993). In the present study, none of the subjects reported any spinal problems despite most of them being very active and motivated towards sports. One subject (LR), who was quite involved with sports at a competitive level, underwent surgery to straighten a mild scoliosis in 1990 and has not had any problems since.

Selective posterior rhizotomy, as a procedure for the alleviation of spasticity, is most effective if the surgery is performed as early as possible. This is in order to avoid having to deal with complications which may set in once a pathological gait pattern has been established in the patient. In such cases, decisions will have to be taken on an

individual basis and the optimum treatment may well be a combination of selective posterior rhizotomy and orthopaedic procedures. (Oppenheim, 1990). The present study has shown that maximum benefits may be accrued by the subject if orthopaedic procedures are used as supplementary corrective procedures to rhizotomy as and when necessary, a view endorsed by Fasano and Broggi (1989).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Eleven adolescents and young adults who underwent selective posterior rhizotomy in 1985 and were part of two previous gait analysis studies, had an evaluation of their gait parameters ten years after surgery. The following conclusions were drawn from this study:

- While there was an increase in the joint ranges of motion when ten year data were compared to the pre-operative data and this was accompanied by a simultaneous decrease in the joint mid-range values, the differences were not statistically significant. When the data were interpreted, taking into account the one year and three year data and data obtained from the age-matched normal controls, the range of motion parameters displayed a positive trend towards the normal range of values.
- There was no statistically significant difference observed when the data obtained from the present study were compared with data from the three year study. Given a hiatus of seven years between evaluation and taking into account the fact that these years marked the adolescent phase in most of the subjects and was characterised by a growth spurt, it may be concluded that the changes brought about by rhizotomy can be considered as permanent.
- There was no significant change in the joint ranges of motion and mid-range values when the ten year data were compared with the data obtained from the age-matched normal controls, indicating that in the long run, the subject is capable of achieving normal ranges

of motion. This finding further affirms the conclusion stated above, that the decrease in muscle tone to normal levels may be permanent.

- There was a significant difference in the spatial-temporal parameters where the patients had lower stride lengths and cadences resulting in decreased velocity, although this finding may have been influenced by the restricted environment where their gait data were gathered
- Selective posterior rhizotomy, when coupled with physiotherapy and appropriate orthopaedic procedures during the early years following surgery, is a useful treatment for the long term alleviation of spasticity and leads to the maintenance and/or improvement in locomotor function for individuals with cerebral palsy.

RECOMMENDATIONS

The present study is the first of its kind in terms of an objective long term follow up gait analysis study. By all accounts, the results obtained in this study confirm the subjective findings of Fasano and Broggi (1989). The following recommendations may be made for future studies and investigations in the area of the long term effects of selective posterior rhizotomy on cerebral palsy.

- Additional long term gait analysis studies from other groups around the world to facilitate comparison of data obtained from present study.
- Detailed kinematic studies as well as electromyographic and force plate studies.
- Three dimensional studies of gait as an extension of the present study.

- Carefully controlled studies in which the effects of other treatment modalities, such as muscle strengthening and orthopaedic procedures, can be evaluated.
- Analyse the changes in the spatial-temporal parameters (stride length, cadence, velocity) for the pre-operative, one year and three year post-operative studies by appropriate normalisation (Hof, 1996) to account for growth changes.

Appendix A

Subject demographic data questionnaire

QUESTIONNAIRE

Date: _____

Dear Parent,

This is to request your consent to videotape _____ for a ten year post-rhizotomy gait analysis study presently being conducted by the Department of Biomedical Engineering, University of Cape Town. In order to proceed with the evaluation, we would be grateful if you could kindly fill in the attached questionnaire and return it in the self-addressed stamped envelope. The date and time of the actual video taping session will be arranged according to your convenience. Your co-operation in this matter is greatly appreciated.

Sincerely,

Dr. C.L Vaughan

Ms. Nivedita Subramanian

-
1. **Name of Patient:** _____
 2. **Present Address:** _____

 3. **Date of Birth:** _____
 4. **Present height in cm:** _____
 5. **Present weight in Kg:** _____
 6. **Date of Rhizotomy:** _____
 7. **Have any orthopaedic procedures been performed after the rhizotomy? If "yes", please provide details. Use back of sheet if necessary**

8. How much physiotherapy has your child been receiving since rhizotomy?

9. How does your child cope with daily activities? (e.g. household movement, shopping, etc.)

10. How has your child been doing at school?

11. Does your child participate in any kind of sporting activities? if "yes", please provide the details.

12. Do you feel that rhizotomy has had a positive effect on your child's overall development? Please explain.

Your Name: _____

Signature: _____

Date: _____

Appendix B

Normal control demographic data questionnaire

QUESTIONNAIRE

Name : _____

Address : _____

Filename : _____

Age : _____

Height : _____

Weight : _____

Have you undergone any orthopaedic procedures during the last two years? If “yes”, please provide details. Use back of sheet if necessary.

Do you suffer from any neurological disorders? If “yes” Please provide details. Use back of sheet if necessary.

I hereby consent to the following gait analysis evaluation procedure.

Signature : _____

Date: _____

Appendix C

Comparison of Camera Systems

COMPARISON OF CAMERA SYSTEMS

In order to verify the validity of gait parameters obtained in the ten year study, it was necessary to compare the output of two systems simultaneously. Two sets of simple experiments were conducted and data were recorded simultaneously by the two systems: the MicronEye digital camera (DigitEyes, Clemson, SC, USA) and a surveillance camera (Burle Security products Ltd., Cork, Ireland) combined with a video cassette recorder (National Panasonic Corp., Japan) used to gather data for two of the patients. While the two systems are known to have different data capture rates (12 Hz for the MicronEye and 25 Hz for the video camera), it was important to establish that they both provided the same spatial (X,Y) coordinates. For the sake of convenience, the digital camera shall be referred to as system 1 while the surveillance camera system shall be referred to as system 2 in this appendix. The experiments designed were: (1) a swinging pendulum to determine the conformity in terms of scaling and (2) a "walking" experiment using three markers attached to a metal frame and moved across the room to mimic gait. The results obtained from each of the studies are presented below.

The Pendulum Test

A pendulum constructed out of electrical wire and a marker was set into motion and the two systems captured data simultaneously. While the number of frames to be captured was pre-set in the case of system 1, digitisation was performed for more than one cycle in system 2, beginning from the point at which system 1 commenced data collection. The extra data points were truncated.

Data from system 1 was converted into ASCII files with the characteristic extension *.asc in order to be utilised in Microsoft Excel. Both sets of data were plotted simultaneously against time yielding a sine curve as shown in Figure C.1.

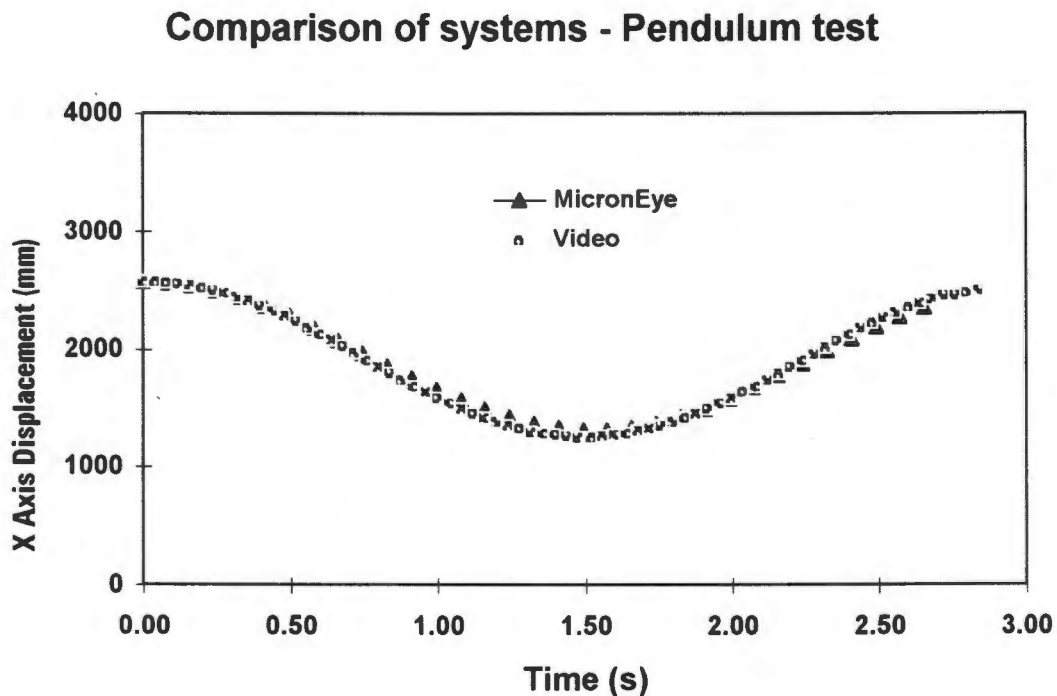


Figure C.1 Simple harmonic motion executed by a pendulum as recorded by the two systems.

As can be seen from Figure C.1, data recorded from both the systems were very similar with respect to displacement and time thus confirming the equivalence of data collected with the two systems.

The Gait Test

Given the restricted space in which to collect data, and the requirement that the MicronEye digital camera required a large distance to the plane of gait, it was necessary to simulate gait by fixing markers onto a stand and move it across the room. Three markers were fixed onto a stand, which was balanced on the left foot. The systems were set into motion and

the stand was moved across the room. The data was subsequently digitised and the output files used in the respective gait analysis programs. The stick figures produced by the simulated walk for both systems are presented in Figures C.2 and C.3.

As can be seen from the figures, it is evident that both systems appeared to be consistent in the ranges, i.e. the distance traversed by the 'leg', although the temporal resolution of the MicronEye system was less than that of the system used for the present study.

Since the structure of the source code did not permit the calculation of angles for this particular set of data (which had a fixed "stiff" knee and hence reported a division by zero error), the sets of data from the two sets were imported into Microsoft Excel and the thigh angle was calculated. A representative section of the thigh angle plotted against time is presented in Figure C.4.

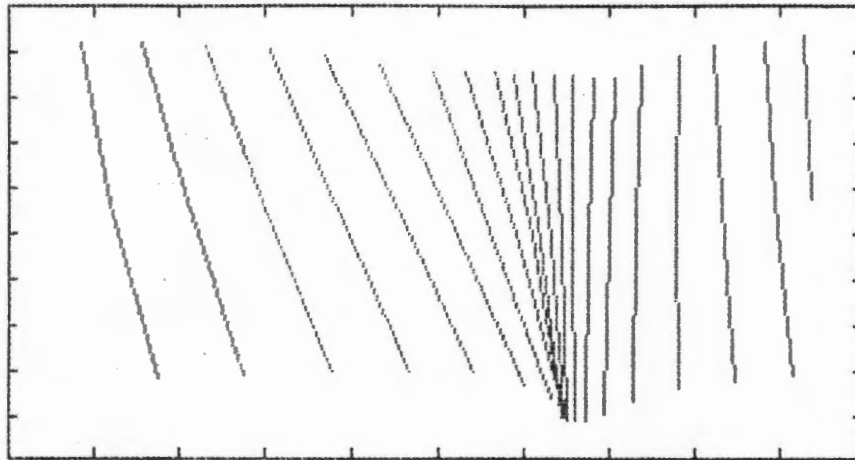
As can be seen from Figure C.4, there is a fair correlation between the two system in the measurement of co-ordinates. The slight shift in angles between the two system may be attributed to the height at which each camera was placed (the MicronEye system was placed at ground level while the video camera was placed at a height of about 1 m from the ground).

STICK FIGURES

Stiff Noddy
9 July 1996
fast walking

walk_1

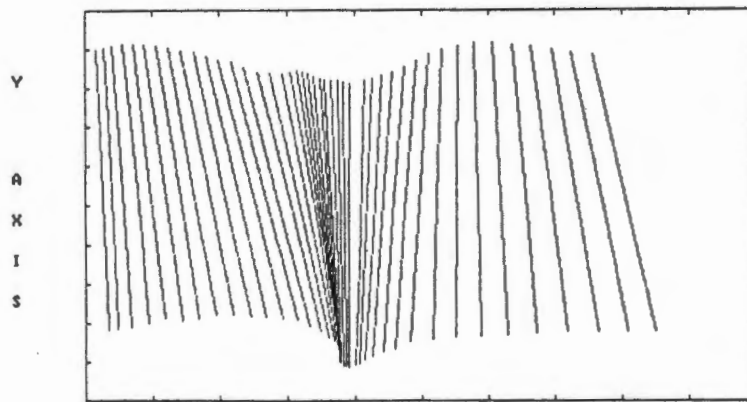
X Range = 912 mm Y Range = 417 mm



(a)

STICK FIGURES

SUBJECT : Test gait
DATE : 9.7.96
COMMENT : Comparison of systems
FILENAME : walk_1.TXT
X Range : 1535.35 mm
Y Range : 481.40 mm



(b)

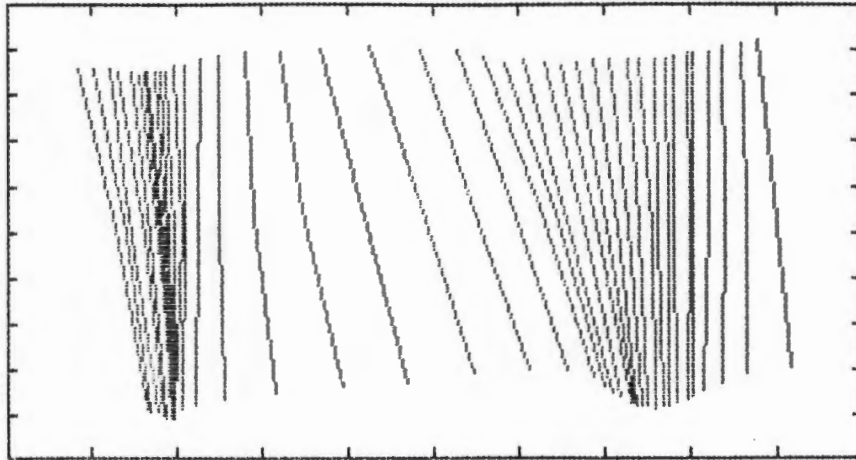
Figure C.2 Stick figures obtained for test gait - fast walking. (a) MicronEye motion detector and (b) VCR system

STICK FIGURES

Stiff Noddy
9 July 1996
very slow walking

walk_2

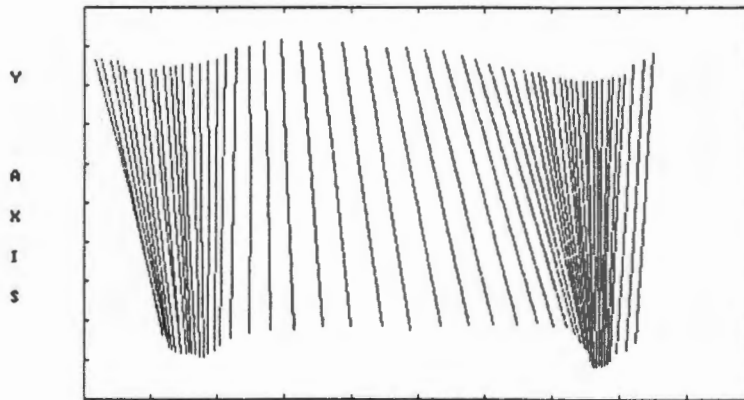
X Range = 850 mm Y Range = 422 mm



(a)

STICK FIGURES

SUBJECT : Test gait
DATE : 9.7.96
COMMENT : Comparison of systems
FILENAME : walk_2.TXT
X Range : 1060.55 mm
Y Range : 446.12 mm



(b)

Figure C.3 Stick figures obtained for test gait - slow walking. (a) MicronEye motion detector and (b) VCR system

Thigh Angle Vs Time

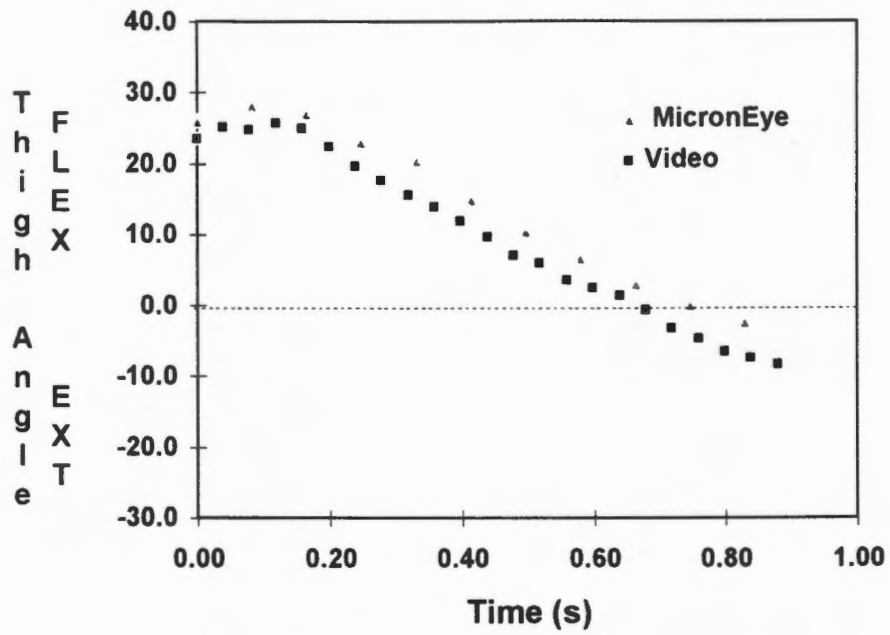


Figure C.4 Thigh angle vs time graph obtained from the two systems.

Appendix D

Conversion software source code

CONVERSION SOFTWARE SOURCE CODE

PROGRAM CONVERT;

{*****}

CONVERT.PAS

AUTHOR : NIVEDITA SUBRAMANIAN
DATE : 29 APRIL 1996

This program written in TurboPascal 5.5 converts the text files and control files obtained from the program 2DGAIT.C and rewrites the data as a single file with all relevant information on the subject. This enables the data to be read either into a spreadsheet or used by the programs GAIT.PAS to calculate the various gait parameters.

{*****}

USES

Crt,
Graph,
Turbo3;

CONST

Done : Boolean=False;
MainMenu : set of Char=['1','2','3','4','5'];

VAR

ErrCode,grDriver,
grMode,HighMode,
LowMode,Counter,
tic,expose_time,
send_time,i,j,
Frame,Marker,
NumberFramesR,
NumberFramesRD,
NumberMarkersR,
NumberFrames,
NumberMarkers,flag : Integer;
Ch : Char;
MissingPoints : array[1..200] of Integer;
FlagFrame : Array[1..200] of Integer;
KneeAngle : array[1..200] of Real;
Thighangle : array[1..200] of Real;
Subject : String[20];
Date : String[20];
Comment : String[40];
Hor : array[1..200] of Integer;
Ver : array[1..200] of Integer;
HorDist,VertDist : Real;

{*****}

VAR

Datafile2 : Array[1..10,1..50] of Real;
ScaleX,ScaleY,ScX : Real;
HorDistR,
RealHor,RealVer,
VertDistR : Real;
ContCoordR : array[1..5,1..10] of Real;
CoordR : Array[1..10,1..200] of real;
CoordRR : Array[1..10,1..200] of real;
XcoordR,YCoordR : Array[1..5,1..200] of real;

```

CoordXR,CoordYR      : Array[1..5,1..200] of real;
Xfiducial,Yfiducial  : Real;

{*****}

PROCEDURE ControlParameters;
VAR
  ControlFileName      : String[12];
  Xdiff,Ydiff          : Real;
  RealHor,RealVer      : Real;
BEGIN
  ClrScr;
  GotoXY(10,10);Write('Enter Filename of Control parameters to be
  read : ');
  Readln(ControlFileName);
  ControlFileName:=ControlFileName+'.TXT';
  Assign(Input,Controlfilename);
  ClrScr;GotoXY(10,10);Write(' R E A D I N G   F R O M   D I S K ');
  Reset(Input);
  FOR i:=1 to 4 DO BEGIN
  FOR j:= 1 to 3 DO BEGIN
  Read (Input,ContcoordR[i,j]);
  END;
  END;
  ClrScr;

  Xdiff:= Abs(ContcoordR[3,2]-contcoordR[2,2]);
  Ydiff:= Abs(contCoordR[1,3]-ContCoordR[3,3]);
  ClrScr;
  If ContCoordR[4,2]>ContCoordR[4,3] THEN BEGIN

  RealHor:=ContCoordR[4,2];
  RealVer:=CContCoordR[4,3];
  END;
  IF ContCoordR[4,2]<ContCoordR[4,3] THEN BEGIN
  RealHor:=ContCoordR[4,3];
  RealVer:=CContCoordR[4,2];
  END;
  IF (Xdiff = 0 ) THEN
  ScaleX:=1 ELSE
  ScaleX:=RealHor/Xdiff;

  IF (YDiff = 0) THEN
  ScaleY:=1 ELSE
  SCAleY:=RealVer/Ydiff;
  ClrScr;
  GotoXY(15,8);Write('SCALING FACTORS');
  GotoXY(10,10);Write('X direction Scaling factor = ',ScaleX:3:2,
  ' mm/pixel');
  GotoXY(10,12);Write('Y direction Scaling factor = ',ScaleY:3:2,
  ' mm/pixel');
  GotoXY(15,15);Write('Hit any key to continue.....');
  Read (Kbd,Ch);
  Assign(input,'');
  Reset(input);
  END;

{*****}

PROCEDURE DataSort;

VAR
  Filenamel           : String[12];

BEGIN
  ClrScr;
  GotoXY(10,12);Write('Enter Filename to be read : ');

```

```

Read(FileName1);
FileName1:=FileName1+'.TXT';
ClrScr;GotoXY(10,10);Write(' R E A D I N G   F R O M   D I S K ');
GotoXY(10,10); Write('Enter Number of Frames Digitised : ');
Readln(NumberFramesR);
GotoXY(10,12); Write('Enter number of Markers used ');
GotoXY(10,14); Write('(upto a maximum of FOUR markers) : ');
Readln(NumberMarkersR);
ClrScr;
Assign(Input, filename1);
Reset(Input);
Clrscr;
FOR Frame:=1 to NumberFramesR DO BEGIN
FOR Marker:=1 to 2*NumberMarkersR DO BEGIN
Read(Input,CoordR[Marker,Frame]);
END;
END;
XFiducial:=CoordR[1,1];
YFiducial:=CoordR[2,1];
FOR Frame := 1 to NumberFramesR DO BEGIN
FOR Marker:=1 to NumberMarkersR DO BEGIN
XCoordR[Marker,Frame]:=CoordR[(2*Marker-1),Frame];
YCoordR[Marker,Frame]:=CoordR[(2*Marker),Frame];
CoordXR[Marker,Frame]:=ScaleX*(XFiducial+
XcoordR[Marker,Frame]-XcoordR[1,Frame]);
CoordYR[Marker,Frame]:=ScaleY*(576-YFiducial-
YcoordR[Marker,Frame]+YCoordR[1,Frame]);
CoordRR[(2*Marker-1),Frame]:=CoordXR[Marker,Frame];
CoordRR[(2*Marker),Frame]:=CoordYR[Marker,Frame];
END;
END;
Assign(input, '');
Reset(input);
END; {OF procedure DataSort}

{*****}

PROCEDURE DeleteExtraFrames;

BEGIN
FlagFrame[1]:=0;Flag:=0;
FOR Frame:=2 to NumberFramesR DO BEGIN
FlagFrame[Frame]:=0;
IF (ABS(CoordRR[3,Frame]-CoordRR[3,Frame-1]))+
(ABS(CoordRR[5,Frame]-CoordRR[5,Frame-1]))+
(ABS(CoordRR[7,Frame]-CoordRR[7,Frame-1])) < 3)
THEN BEGIN
FlagFrame[Frame]:=1;
Flag:=Flag+1;
END;
END;
END;

{*****}

VAR
Filename3           : String[12];
SubjectR            : String[20];
DateR               : String[20];
CommentR            : String[40];
Send_timerR,Expose_timerR : Integer;

BEGIN
ClrScr;
ControlParameters;
DataSort;
DeleteExtraFrames;

```

```

NumberFramesRD:=NumberFramesR-(Flag+1);
GotoXY(10,10); Write('Enter name of subject : ');
Readln(SubjectR);
GotoXY(10,12); Write('Enter Date : ');
Readln(DateR);
GotoXY(10,14); Write('Enter Comments : ');
Readln(CommentR);
GotoXY(10,16); Write('Enter Send_Time : ');
Readln(Send_TimeR);
GotoXY(10,18); Write('Enter Expose_Time : ');
Readln(Expose_TimeR);
GotoXY(20,20); Write('Hit any key to continue.....');
Read(Kbd,ch);
Assign(output,'');
rewrite(output);
ClrScr;
GotoXY(10,12);Write('Enter Name of Output file in which to
enter');
GotoXY(10,14);Write('relevant normalised subject information:');
Readln(Filename3);
Filename3:=Filename3+'.TXT';
Assign(output,Filename3);
Rewrite(output);
WriteLn(Output,SubjectR);
WriteLn(Output,DateR);
WriteLn(Output,CommentR);
Write(Output,Send_TimeR);
WriteLn(Output,' { Send Time } ');
Write(Output,Expose_TimeR);
WriteLn(Output,' { Expose Time } ');
Write(Output,NumberFramesRD);
WriteLn(Output,' { Number of Frames } ');
Write(Output,NumberMarkersR);
WriteLn(Output,' { Number of Markers } ');
Write(Output,ScaleX:3:2);
WriteLn(Output,' { X Scaling Factor } ');
Write(Output,ScaleY:3:2);
WriteLn(Output,' { Y Scaling Factor } ');
FOR Frame:= 1 to NumberFramesR-1 DO BEGIN
FOR Marker:=1 to 2*NumberMarkersR DO BEGIN
IF FlagFrame[Frame]=0 THEN
Write(Output,CoordRR[Marker,Frame] :3:2,' ');
END;
Writeln;
END;
ClrScr;
Close(Input);
Close(Output);

```

END.

Appendix E

Gait Analysis software source code

```

{$R-}      {Range checking off}
{$B+}      {Boolean complete evaluation on}
{$S+}      {Stack checking on}
{$I+}      {I/O checking on}
{$N-}      {No numeric coprocessor}
{$M 65500,16384,655360} {Turbo 3 default stack and heap}

```

```
PROGRAM GAITANALYSIS;
```

```
{*****}
```

```
GAIT ANALYSIS
```

```

AUTHORS : KIT VAUGHAN, JEREMY O'CONNOR
          and NIVEDITA SUBRAMANIAN
DATE    : 17 MARCH 1996

```

This program, written in Turbo Pascal 5.5, is designed for use with the data generated by the programs 2DGAIT.EXE and CONVERT.EXE. Its purpose is to display these data in a variety of formats as well as output the knee and thigh angle data into a textfile and calculate all relevant gait parameters.

```
{*****}
```

```
Uses
```

```

  Crt, {Unit found in TURBO.TPL}
  Graph,
  Turbo3; {Unit found in TURBO3.TPU}

```

```
CONST
```

```

  Done           :Boolean=False;
  IOErr          :Boolean=False;
  IOVal          :Integer=0;
  Menu           :set of Char=['1','2','3','4','5','6','7','8','9','X'];

```

```
TYPE
```

```
DATA = array[1..5,1..50] of Real;
```

```
VAR
```

```

  ErrCode,grDriver,grMode,
  LowMode,HighMode,
  expose_time,
  send_time,
  FrameStart,FrameEnd,
  MarkerStart,MarkerEnd,
  Frame,Marker,
  NumberFrames,
  Counter,
  NumberMarkers,
  X,expose_timeR           :Integer;
  send_timeR              :Integer;
  NumberFramesR           :Integer;
  NumberMarkersR          :Integer;
  ScX,ScY                 :Array[1..10] of real;
  XTicVal,YTicVal         :Array[1..10] of string;
  ScaleX,ScaleY           :Real;
  Hor,Ver                 :Array[1..250] of Integer;
  MaxKneeAngle,
  MaxTHighAngle,
  MinKneeAngle,

```

```

MinThighAngle,
ThighMidPt,
KneeMidPt,
Areal,AreaX,
Area,Periml,
Perimtr,Perimeter,
ThighMaxl,THighMinl,
KneeMaxl,KneeMinl,
KneeROM,THighROM,
HorR,VerR           :Real;
HorStr,VerStr       :String[10];
KneeAngle,
ThighAngle          :array[1..250] of Real;
Ch                  :Char;
MissingPoints       :array[1..250] of Boolean;
Xcoord              :array[1..5,1..250] of Real;
Ycoord              :array[1..5,1..250] of Real;
VelX,VelY           :array[1..5,1..250] of Real;
AccX,AccY           :array[1..5,1..250] of Real;
Subject             :String[20];
Date                :String[20];
Comment             :String[40];
DiskFlag            :String[5];
FileName            :String[12];
AHR,AVR             :String[7];
Xleft,Xright,
Ytop,Ybottom,
HorPlotRange,
VerPlotRange,
ActualHorRange,
ActHorRange,
ActVerRange,
ActualVerRange     :Real;
Out : Text;

{*****}

PROCEDURE TalkToDisk;

{This subprogram either reads from the disk or writes to the disk
depending on how the DiskFlag is set}

VAR
    HorPlotRange,
    VerPlotRange     :Real;
    SubjectR         :String[20];
    DateR            :String[20];
    CommentR         :String[40];
    XcoordR          :array[1..5,1..250] of Real;
    YcoordR          :array[1..5,1..250] of Real;
    CoordR           :array[1..10,1..250] of Real;

BEGIN
    ClrScr;
    GotoXY(10,10);Write('Enter filename to be read : ');
    Assign(Input,'');
    Reset(Input);
    Read(FileName);
    FileName:=FileName + '.TXT';ClrScr;
    Assign(Input, FileName);
    Reset(Input);
    ClrScr;GotoXY(10,10);Write('R E A D I N G   F R O M   D I S K ');
    Readln(Input,SubjectR);
    Readln(Input,DateR);
    Readln(Input,CommentR);
    Readln(Input,Send_timer);
    Readln(Input,Expose_Timer);
    Readln(Input,NumberFramesR);

```

```

Readln(Input,NumberMarkersR);
Readln(Input,ScaleX);
Readln(Input,ScaleY);
FOR FRAME := 1 to NumberFramesR DO BEGIN
FOR Marker:= 1 to 2*NumberMarkersR DO BEGIN
Read(Input,CoordR[Marker,Frame]);
END;
END;

  expose_time:=expose_timeR;
  send_time:=send_timeR;
  NumberFrames:=NumberFramesR;
  FrameEnd:=NumberFrames;
  NumberMarkers:=NumberMarkersR;
  MarkerEnd:=NumberMarkers;
  Subject:=SubjectR;
  Date:=DateR;
  Comment:=CommentR;

  FOR Frame :=1 TO NumberFrames DO BEGIN
    FOR Marker:=1 TO NumberMarkers DO BEGIN
      XCoord[Marker,Frame]:=CoordR[(2*Marker-1),Frame];
      YCoord[Marker,Frame]:=CoordR[(2*Marker),Frame];
    END; {of marker loop}
  END; {of frame loop}
END;{of procedure TalkToDisk}

{*****}

PROCEDURE ReadDataFromDisk;

{This subprogram first reads a data file from disk and then checks to
see if there are any missing points (the frame number is then
flagged), and finally the minimum and maximum values for X and Y are
identified}

BEGIN
  DiskFlag:='Read';
  TalkToDisk;ClrScr;
  FOR Frame:=1 TO NumberFrames DO BEGIN
    MissingPoints[Frame]:=FALSE;
    FOR Marker:=1 TO NumberMarkers DO BEGIN
      IF (Xcoord[Marker,Frame]=0) OR (Ycoord[Marker,Frame]=0)
        THEN MissingPoints[Frame]:=TRUE;
    END; {of marker loop}
  END; {of frame loop}
  ClrScr;GotoXY(10,10);
  Xleft:=Xcoord[1,1];Xright:=Xcoord[1,1];
  Ytop:=Ycoord[1,1];Ybottom:=Ycoord[1,1];
  FOR Frame:=1 TO NumberFrames DO BEGIN
    IF NOT MissingPoints[Frame] THEN BEGIN
      FOR Marker:=1 TO NumberMarkers DO BEGIN
        IF Xcoord[Marker,Frame]<Xleft THEN Xleft :=Xcoord[Marker,Frame];
        IF Xcoord[Marker,Frame]>Xright THEN Xright :=Xcoord[Marker,Frame];
        IF Ycoord[Marker,Frame]<Ybottom THEN Ybottom:=Ycoord[Marker,Frame];
        IF Ycoord[Marker,Frame]>Ytop THEN Ytop :=Ycoord[Marker,Frame];
      END; {of marker loop}
    END; {of if loop}
  END; {of frame loop}
  ActualHorRange:=Xright-Xleft; HorPlotRange:=1.2*ActualHorRange;
  ActualVerRange:=Ytop-Ybottom; VerPlotRange:=1.2*ActualVerRange;
  Str(HorPlotRange:3:2,AHR);
  Str(VerPlotRange:3:2,AVR);
END; {of procedure ReadDataFromDisk}

{*****}

```

```

PROCEDURE CalculateAngles;

{This Program calculates the Knee and Thigh angles given the
coordinates of the hip, knee and ankle.}

TYPE
Data = RECORD
END;

VAR
ShankX,ShankY,
ThighX,ThighY,
VerX,VerY,
Sign,Ratio,
ThighLength,
ShankLength,pi      :Real;
fwbk                 :Integer;

DataFile2            :File OF Real;

Begin
pi:=3.141592;
ClrScr;
assign(input,'');
Reset(input);
GotoXY(5,10);Write('Is this forward or backward walking?');
GotoXY(5,12);Write('Enter 1 for forward and 2 for backward : ');
Read(fwbk);
Clrscr;
GotoXY(5,10);
Write('CALCULATING KNEE , THIGH ANGLES ');
GotoXY(15,15);Write('Dont even think about messing with the
keyboard!!!!');
IF XCoord[2,1] < XCoord[2,NumberFrames] THEN sign:=+1;
IF XCoord[2,1] > XCoord[2,NumberFrames] THEN sign:=-1;
IF fwbk=2 THEN sign:=(-1)*sign;
For Counter:= 1 to NumberFrames DO BEGIN
For Frame:=1 To NumberFrames DO BEGIN
ShankX:=XCoord[4,Frame]-XCoord[3,Frame];
ShankY:=YCoord[4,Frame]-YCoord[3,Frame];
ThighX:=XCoord[3,Frame]-XCoord[2,Frame];
ThighY:=YCoord[3,Frame]-YCoord[2,Frame];
VerX:=0;VerY:=-1;
ThighLength:=Sqrt(ThighX*ThighX+ThighY*ThighY);
ratio:=(shankX*ThighY-ShankY*ThighX)/
(ThighLength*Sqrt(ShankX*ShankX+ShankY*ShankY));
KneeAngle[Frame]:=sign*ArcTan(ratio/sqrt(1-ratio*ratio))*180/pi;
IF KneeAngle[Frame]>0 THEN KneeAngle[Frame]:=(-1)*KneeAngle[Frame];
ratio:=(VerX*ThighY-VerY*ThighX)/thighLength;
ThighAngle[Frame]:=Sign*ArcTan(ratio/Sqrt(1-ratio*ratio))*180/pi;
END;
END;
KneeMax1:=KneeAngle[1];
KneeMin1:=KneeAngle[1];
ThighMax1:=ThighAngle[1];
ThighMin1:=ThighAngle[1];
For Frame:= 1 TO NumberFrames DO BEGIN

IF KneeAngle[Frame]>KneeMax1 THEN MaxKneeAngle:=KneeAngle[Frame]
ELSE
MaxKneeAngle:=KneeMax1;
KneeMax1:=MaxKneeAngle;

IF KneeAngle[Frame]<KneeMin1 THEN MinKneeAngle:=KneeAngle[Frame]
ELSE
MinKneeAngle:=KneeMin1;
KneeMin1:=MinKneeAngle;

```

```

IF ThighAngle[Frame]>ThighMax1 THEN MaxThighAngle:=ThighAngle[Frame]

ELSE
MaxThighAngle:=ThighMax1;
ThighMAX1:=MaxThighAngle;

IF ThighAngle[Frame]<ThighMin1 THEN MinThighAngle:=ThighAngle[Frame]
ELSE
MinThighAngle:=ThighMin1;
ThighMin1:=MinThighAngle;
END;

END; {Of Procedure CalculateAngles}

{*****}

PROCEDURE WriteAnglestoDisk;
VAR
  FileName2      :String[12];
  Time           :real;
BEGIN
  ClrScr;
  Time:=0-(expose time/1000);
  assign(input,'');
  Reset(input);
  GotoXY(10,10); Write ('Have you calculated the angles yet ? (Y/N)
');
  Read(Kbd,Ch);; CLrScr;
  if Ch IN ['n','N'] then CalculateAngles;
  ClrScr;
  GotoXY(10,10);Write('Hit any key to continue.....');
  Read(Kbd,Ch);ClrScr;
  assign(input,'');
  reset(input);
  GotoXY(10,10); Write ('Enter name of file to write Angle Data: ');
  Readln(FileName2);
  FileName2:=FileName2+'.txt';
  Assign(output,FileName2);
  Rewrite(output);
  Writeln(Subject);
  Writeln(Date);
  Writeln(Comment);
  Writeln(FileName);
  Write('Time',' ','Knee ',' ','Thigh ');
  Writeln;
  For Frame:= 1 to NumberFrames DO BEGIN
  Time:=Time+(Expose Time/1000);
  Write(Output,Time:2:2,' ',ABS(KneeAngle[Frame]):3:2,' ',
  30+ThighAngle[Frame]:3:2);
  Writeln;
  End;
  assign(output,'');
  rewrite(output);
  END; {Of Procedure WriteAngles to Disk}

{*****}

PROCEDURE PlotHeadingForAngles;

{This subprogram prints out the heading information, the horizontal
and vertical ranges, and then plots the boundaries and tic marks of
the actual plotting area}

VAR
  cntr,Xtic,Ytic :Integer;
BEGIN
DetectGraph(grDriver,grMode);
grDriver:=Detect;

```

```

ErrCode:=GraphResult;
if ErrCode=grOK then

BEGIN

GetModeRange(grDriver,LowMode,HighMode);
SetGraphMode(HighMode);
  SetColor(15);
  OutTextXY(40,25, 'SUBJECT:');
  OutTextXY(140,25,Subject);
  OutTextXY(40,50, 'DATE:');
  OutTextXY(140,50,Date);
  OutTextXY(40,75, 'COMMENT:');
  OutTextXY(140,75,Comment);
  OutTextXY(40,100, 'FILENAME:');
  OutTextXY(140,100,Filename);
  SetColor(15);
  Line(100,150,600,150);
  Line(600,150,600,390);
  Line(600,390,100,390);
  Line(100,390,100,150);
  END;
END; {of procedure PlotHeadingForAngles}

{*****}

PROCEDURE PlotHeading;
{This subprogram prints out the heading information, the horizontal
and vertical ranges, and then plots the boundaries and tic marks of
the actual plotting area}

VAR
  cntr,Xtic,Ytic :Integer;

BEGIN

DetectGraph(grDriver,grMode);
grDriver:=Detect;
ErrCode:=GraphResult;
if ErrCode=grOK then

BEGIN
GetModeRange(grDriver,LowMode,HighMode);
SetGraphMode(HighMode);
SetColor(15);
  OutTextXY(40,35, 'SUBJECT  :');
  OutTextXY(140,35,Subject);
  OutTextXY(40,50, 'DATE    :');
  OutTextXY(140,50,Date);
  OutTextXY(40,65, 'COMMENT  :');
  OutTextXY(140,65,Comment);
  OutTextXY(40,80, 'FILENAME :');
  OutTextXY(140,80,Filename);
  OutTextXY( 40,100, 'X Range  : ');
  OutTextXY( 140,100,AHR);
  OutTextXY( 190,100, ' mm');
  OutTextXY(40,115, 'Y Range  : ');
  OutTextXY(140,115,AVR);
  OutTextXY( 190,115, ' mm');
  OutTextXY(325,425, 'X   A X I S   (mm) ');
  OutTextXY(45,190, 'Y');
  OutTextXY(45,250, 'A');
  OutTextXY(45,275, 'X');
  OutTextXY(45,300, 'I');
  OutTextXY(45,325, 'S');
  SetColor(15);
  Line(100,150,600,150);Line(600,150,600,390);
  Line(600,390,100,390);Line(100,390,100,150);
  FOR cntr:=1 TO 9 DO BEGIN

```

```

        Xtic:=cntr*50;Ytic:=cntr*24;
        Line(100,150+Ytic,103,150+Ytic);
        Line(100+Xtic,150,100+Xtic,153);
        Line(600,150+Ytic,597,150+Ytic);
        Line(100+Xtic,390,100+Xtic,387);
    END; {of cntr loop}
END;
END; {of procedure PlotHeading}

{*****}

PROCEDURE GetPlotCoords
(VAR Marker,Frame,Xplot,Yplot :Integer);
{This subprogram scales the two plotting coordinates so that they
fall within the range (150,390) and (100,600). }

BEGIN

    Xplot:=Round(150-250*(HorPlotRange-ActualHorRange)/HorPlotRange+
                500*(Xcoord[Marker,Frame]-Xleft)/HorPlotRange);
    Yplot:=Round(390-120*(VerPlotRange-ActualVerRange)/VerPlotRange-
                240*(Ycoord[Marker,Frame]-Ybottom)/VerPlotRange);

    {
        For X:= 1 to 9 DO BEGIN
            ScX[X]:=(HorPlotRange/10)*X;
            ScY[X]:=(VerPlotRange/10)*X;
            Str(ScX[X]:3:0,XTicVal[X]);
            Str(ScY[X]:3:0,YTicVal[X]);
        END;
    }

END; {of procedure GetPlotCoords}

{*****}

FUNCTION InWindow (Marker,Frame,X,Y: INTEGER):BOOLEAN;
BEGIN
    IF (X >= 100) AND (X < 604) AND (Y >= 150) AND (Y < 384) AND
(Xcoord[Marker,Frame]<>100) AND (Ycoord[Marker,Frame]<>150)
    THEN InWindow:= TRUE
    ELSE InWindow:= FALSE;
END;

{*****}

PROCEDURE PlotRawData;
{This subprogram simply plots the raw data}

VAR
    X,Y      :Integer;

BEGIN
    DetectGraph(grDriver,grMode);
    InitGraph(grDriver,grMode,' ');
    ErrCode:=GraphResult;
    if ErrCode=grOK then BEGIN
        GetModeRange(grDriver,LowMode,HighMode);
        SetGraphMode(HighMode);
        {SetColor(15);}
        OutTextXY(280,10,'RAW DATA');
        OutTextXY(280,12,'_____');
        PlotHeading;
        FOR Frame:=FrameStart TO FrameEnd DO BEGIN
            FOR Marker:=MarkerStart TO MarkerEnd DO BEGIN
                GetPlotCoords(Marker,Frame,X,Y);
                IF InWindow (Marker,Frame,X,Y) THEN
                    SetColor(15);
                    Circle(X,Y,1);
            END; {of marker loop}
        END; {of frame loop}
    END;
END;

```

```

    Read(Kbd,Ch);TextMode(LastMode);
    {! 3. The Textmode procedure requires a parameter (Mode:Word) in
    Turbo 5.0.}
    END;
    END; {of procedure PlotRawData}

    {*****}

    PROCEDURE PlotStickFigures;
    {This subprogram allows the user to join every marker to any other
    marker (in each frame), thus yielding a stick figure effect}

    VAR

        X1,X2,Y1,Y2      :Integer;
        MarkerJoin       :array[1..5] of Integer;

    BEGIN

        Assign(input, '');
        Reset(input);
        ClrScr;
        GotoXY(10,4);Write('To plot stick figures you must indicate');
        GotoXY(10,6);Write('how the markers are joined to each other');
        GotoXY(10,9);Write('Enter the marker number when prompted');
        GotoXY(10,11);Write('If a marker is not joined then enter "0"');
        FOR Marker:=MarkerStart TO MarkerEnd DO BEGIN
            REPEAT
                GotoXY(3,12+2*Marker);
                Write('Marker number ',Marker,' is joined to marker : ');
                Read(MarkerJoin[Marker]);
                UNTIL MarkerJoin[Marker] <= NumberMarkers;
            END; {of marker loop}
            DetectGraph(grDriver,grMode);
            InitGraph(grDriver,grMode, '');
            ErrCode:=GraphResult;
            if ErrCode=grOK then
                BEGIN
                    GetModeRange(grDriver,LowMode,HighMode);
                    SetGraphMode(HighMode);
                    OutTextXY(280,10,'STICK FIGURES');
                    OutTextXY(280,12,'_____');
                    PlotHeading;
                    SetColor(15);
                    FOR Frame:=FrameStart TO FrameEnd DO BEGIN
                        FOR Marker:=MarkerStart TO MarkerEnd DO BEGIN
                            IF MarkerJoin[Marker] <> 0 THEN BEGIN
                                GetPlotCoords(Marker,Frame,X1,Y1);
                                GetPlotCoords(MarkerJoin[Marker],Frame,X2,Y2);
                                IF InWindow (Marker,Frame,X1,Y1) AND
                                    InWindow (Marker,MarkerJoin[Marker],X2,Y2) THEN
                                    Line(X1,Y1,X2,Y2);
                            END; {of IF loop}
                        END; {of marker loop}
                    END; {of frame loop}
                END;
            Read(Kbd,Ch);TextMode(LastMode);
            {! 4. The Textmode procedure requires a parameter (Mode:Word) in
            Turbo 5.0.}
            END; {of procedure PlotStickFigures}

            {*****}

```

```
PROCEDURE PlotTrajectories;
{This subprogram joins up the data points for each marker from
adjacent frames, thus providing a plot of the trajectories}
```

```
VAR
```

```
    NextFrame,
    X1,X2,
    Y1,Y2      :Integer;
```

```
BEGIN
```

```
    DetectGraph(grDriver,grMode);
    InitGraph(grDriver,grMode,'');
    ErrCode:=GraphResult;
    if ErrCode=grOK then
    BEGIN
    GetModeRange(grDriver,LowMode,HighMode);
    SetGraphMode(HighMode);
    OutTextXY(280,10,'TRAJECTORIES');
    OutTextXY(280,12,'_____');
    PlotHeading;
    SetColor(15);
    FOR Marker:=MarkerStart TO MarkerEnd DO BEGIN
        FOR Frame:=FrameStart TO FrameEnd-1 DO BEGIN
            NextFrame:=Frame+1;
            GetPlotCoords(Marker,Frame,X1,Y1);
            GetPlotCoords(Marker,NextFrame,X2,Y2);
        IF InWindow(Marker,Frame,X1,Y1) AND InWindow(Marker,NextFrame,X2,Y2)
            THEN Line(X1,Y1,X2,Y2);
        END; {of frame loop}
    END; {of marker loop}
    END;
    Read(Kbd,Ch);TextMode(LastMode);
    {! 5. The Textmode procedure requires a parameter (Mode:Word) in
Turbo 5.0.}
    END; {of procedure PlotTrajectories}
```

```
{*****}
```

```
PROCEDURE PlotDataCurves;
```

```
{This subprogram plots the horizontal and vertical datapoints,
joining adjacent frames and thus producing a curve.}
```

```
BEGIN
```

```
for Frame:=1 TO NumberFrames-1 DO BEGIN
IF (Hor[Frame ]>99) AND (Hor[Frame ]<601) AND
(Hor[Frame+1]>99) AND (Hor[Frame+1]<601) AND
(Ver[Frame ]>149) AND (Ver[Frame ]<391) AND
(Ver[Frame+1]>149) AND (Ver[Frame ]<391) THEN
BEGIN
    DetectGraph(grDriver,grMode);
    ErrCode:=GraphResult;
    If ErrCode=grOk Then
    BEGIN
        GetModeRange(grDriver,LowMode,HighMode);
        SetColor(15);
        SetLineStyle(SolidLn,0,NormWidth);
        Line(Hor[Frame],Ver[Frame],Hor[Frame+1],Ver[Frame+1]);
    END; {of IF Loop}
    END; {of Frame Loop};
END;
Read(Kbd,Ch);
TextMode(LastMode);
END; {OF Procedure PlotDataCurves}
```

```
{*****}
```

```
PROCEDURE PlotThighonYaxis;
```

```
{This subprogram plots the tic marks for the Y axis, labels the axis,  
and then assigns the vertical plotting data for the array Ver, using  
the thigh angle data.}
```

```
VAR
```

```
X,Y,counter,tic : Integer;
```

```
BEGIN
```

```
DetectGraph(grDriver,grMode);  
ErrCode:=GraphResult;  
if ErrCode=grOK then BEGIN  
  GetModerange(grDriver,lowMode, HighMode);  
  For counter:=1 to 7 DO BEGIN  
    SetColor(15);  
    tic:=Round(counter*240/7);  
    Line(99,150+tic,101,150+tic);  
    Line(600,150+tic,598,150+tic);  
  END;  
  SetLineStyle(DottedLn,0,NormWidth);  
  Line(100,287,600,287);  
  SetColor(15);  
  OutTextXY(75,150,'40');  
  OutTextXY(50,190,'T');  
  OutTextXY(50,200,'H F');  
  OutTextXY(50,210,'I L');  
  OutTextXY(50,220,'G E');  
  OutTextXY(50,230,'H X');  
  OutTextXY(75,286,'O');  
  OutTextXY(50,296,'A');  
  OutTextXY(50,306,'N');  
  OutTextXY(50,316,'G E');  
  OutTextXY(50,326,'L X');  
  OutTextXY(50,336,'E T');  
  OutTextXY(75,390,'30');  
  For Frame:=1 to NumberFrames DO BEGIN  
    Ver[Frame]:=390-Round((ThighAngle[Frame]+30)*240/70);  
  END; {of Frame Loop}  
END;  
END; { Of Procedure PlotThighOnYaxis}
```

```
{*****}
```

```
PROCEDURE PlotKneeonYaxis;
```

```
{This subprogram plots the tic marks for the Y axis, labels the axis,  
and then assigns the vertical plotting data for the array Ver, using  
the knee angle data.}
```

```
VAR
```

```
counter,tic : Integer;
```

```
BEGIN
```

```
DetectGraph(grDriver,grMode);  
ErrCode:=GraphResult;  
if ErrCode=grOK then BEGIN  
  GetModerange(grDriver,lowMode, HighMode);  
  {SetGraphMode(HighMode);}  
  For counter:=1 to 9 DO BEGIN  
    SetColor(15);  
    tic:=counter*24;  
    SetLineStyle(dottedLn,0,NormWidth);  
    Line(99,150+tic,101,150+tic);
```

```

Line(600,150+tic,598,150+tic);
END;
Line(100,270,600,270);
Line(100,366,600,366);
SetColor(15);
OutTextXY(75,150,'90');
OutTextXY(50,200,'K F');
OutTextXY(50,210,'N L');
OutTextXY(50,220,'E E');
OutTextXY(50,230,'E X');
OutTextXY(75,265,'40');
OutTextXY(50,296,'A');
OutTextXY(50,306,'N E');
OutTextXY(50,316,'G X');
OutTextXY(50,326,'L T');
OutTextXY(50,336,'E');
OutTextXY(75,364,' O');
OutTextXY(75,390,'10');
For Frame:=1 to NumberFrames DO BEGIN
Ver[Frame]:=390+Round((KneeAngle[Frame])*240/100);
END;
END;
END; {of procedure PlotKneeOnYaxis}

{*****}

PROCEDURE PlotThighOnXaxis;
{This subprogram plots the tic marks for the X axis, labels the axis,
and then assigns the horizontal plotting data for the array Hor,
using the thigh angle Data}

VAR

tic,counter      : Integer;

BEGIN

DEtectGraph(grDriver,grMode);
TextColor(14);
ErrCode:=GraphResult;
if ErrCode<>grOK THEN
BEGIN
GetModeRange(grDriver,LowMode,HighMode);
FOR Counter :=1 to 6 DO BEGIN
tic:=Round(counter*500/7);
Line(100+tic,150,100+tic,152);
Line(100+tic,390,100+tic,388);
END;
SetLineStyle(dottedLn,0,Normwidth);
Line(314,150,314,390);
SetColor(15);
OutTextXY(95,400,'30');
OutTextXY(200,400,'EXT');
OutTextXY(313,400,'0');
OutTextXY(450,400,'FLEX');
OutTextXY(597,400,'40');
OutTextXY(300,420,'THIGH ANGLE(degrees)');
FOR Frame:=1 TO NumberFrames DO BEGIN
Hor[Frame]:=100+Round((ThighAngle[Frame]+30)*500/70);
END; {of frame loop}
END;
END; {of Procedure PlotThighOnXaxis}

{*****}

```

```

PROCEDURE PlotTimeOnXaxis;

{This subprogram plots the tic marks for the X axis, labels the Axis
and then assigns the horizontal plotting data to the array HOR using
the time data}

VAR

    Counter,tic           :Integer;
    TimePlotRange        : Real;

BEGIN

    DetectGraph(grDriver,grMode);
    ErrCode:=GraphResult;
    If ErrCode<>grOK THEN BEGIN
    GetModeRange(grDriver,LowMode,HighMode);
    If NumberFrames<=40 THEN TimePlotRange:=2;
    If NumberFrames>=40 THEN TimePlotRange:=3;
    SetLineStyle(SolidLn,0,NormWidth);
    FOR Counter:=1 TO Round(2*TimePlotRange)-1 DO BEGIN
    Tic:=Round(Counter*250/TimePlotRange);
    Line(100+tic,150,100+tic,152);
    Line(100+tic,390,100+tic,388);
    END; {of counter loop}
    GotoXY(75,85);
    If TimePlotRange=2 THEN BEGIN
    SetColor(15);
    OutTextXY(100,395,'0');
    OutTextXY(350,395,'1');
    OutTextXY(600,395,'2');
    OutTextXY(340,415,'TIME(s)');
    END; {Of Labelling IF}
    If TimePlotRange=3 THEN BEGIN
    OutTextXY(100,395,'0');
    OutTextXY(266,395,'1');
    OutTextXY(432,395,'2');
    OutTextXY(598,395,'3');
    OutTextXY(340,415,'TIME (s)');
    END; {of Labelling IF}
    For Frame:=1 to NumberFrames DO BEGIN
    Hor[Frame]:=100+Round(0.5*(INT(Frame)-1)*(INT(send_time+expose_time))
    / TimePlotRange);
    END; {of Frame Loop}
    END; {Of Procedure PlotTimeOnXaxis}
    END;

{*****}

PROCEDURE PlotKneeVsTime;

{This subprogram plots the knee angle versus time.}

BEGIN

DetectGraph(grDriver,grMode);
InitGraph(grDriver,grMode,'');
ErrCode:=GraphResult;
IF ErrCode=grOK then BEGIN
    GetModeRange(grDriver,LowMode,HighMode);
    setGraphMode(HighMode);
    SetColor(15);
    OutTextXY(250,5,'KNEE ANGLE Vs. TIME');
    PlotHeadingForAngles;
    PlotTimeOnXaxis;
    PlotKneeOnYaxis;
    PlotDataCurves;

```

```

END; {of IF loop}
END; {of procedure PlotKneeVsTime}

{*****}

PROCEDURE PlotThighVsTime;

{This Subprogram plots the thigh angle vs time.}

BEGIN

DetectGraph(grDriver,grMode);
InitGraph(grDriver,grMode,'');
ErrCode:=GraphResult;
IF ErrCode=grOK then BEGIN
  GetModeRange(grDriver,LowMode,HighMode);
  setGraphMode(HighMode);
  OutTextXY(250,5,'THIGH ANGLE Vs. TIME');
  PlotHeadingForAngles;
  PlotTimeOnXaxis;
  PlotThighOnYAxis;
  PlotDataCurves;
  END; {Of IF loop}
  END; {Of Procedure PlotThighVsTime};

{*****}

PROCEDURE PlotKneeVsThigh;

{This subprogram plots the Knee angle Vs the Thigh Angle}

BEGIN

DetectGraph(grDriver,grMode);
InitGraph(grDriver,grMode,'');
ErrCode:=GraphResult;
if ErrCode=grOK then BEGIN
  GetModeRange(grDriver,LowMode,HighMode);
  SetGraphMode(HighMode);
  OutTextXY(250,5,'KNEE ANGLE Vs. THIGH ANGLE');
  PlotHeadingForAngles;
  PlotThighOnXaxis;
  PlotKneeOnYAxis;
  PlotDataCurves;
  END; {Of IF loop}
  END; {of Procedure PlotKneeVsThigh}

{*****}

PROCEDURE PlotAngles;

{ This subprogram enables the user to plot the knee and thigh angles
in avariety of combinations}

CONST

  DonePlot      : Boolean=False;
  PlotMenu      : set of Char=['1','2','3','4','5'];

BEGIN

  WHILE NOT DonePlot DO BEGIN
    REPEAT
      ClrScr;
      GotoXY(30,5);Write('PLOT MENU');
      GotoXY(25,9);Write('(1) Calculate Angles');
      GotoXY(25,11);Write('(2) Knee Angle vs time');
      GotoXY(25,13);Write('(3) Thigh Angle vs time');
      GotoXY(25,15);Write('(4) Knee Angle vs Thigh Angle');

```

```

        GotoXY(25,17);Write('(5) Return to Display Menu');
        GotoXY(30,20);Write('Enter your choice now  :');
        Read(kbd,ch)
        UNTIL Ch IN PlotMenu;
CASE Ch OF
'1'   : CalculateAngles;
'2'   : PlotKneeVsTime;
'3'   : PlotThighVsTime;
'4'   : PlotKneeVsThigh;
'5'   : DonePlot:=True
END;{of case}
END; {of while};
DonePlot:=False;
END; {Of PROCEDURE PlotAngles}

{*****}

PROCEDURE TemporalData;

{This subprogram calculates cycle time, Cadence, Stride Length and
average Speed}

VAR

    Sum                : Array[1..5] of Real;
    Min, CycleTime,
    Cadence, StrideLength,
    AverageSpeed,
    NumberTurningPoints : Real;
    LoopCntr,CpCntr,MinCntr,
    CyclePeriod,NextFrame,
    EstCyclePeriod,Offset : Integer;

BEGIN
    ClrScr;
    GotoXY(10,5); Write('The Temporal Data may be calculated');
    GotoXY(10,7); Write('from the Thigh Angle Vs. time Graph. ');
    GotoXY(10,9); Write('Have You calculated the angle data yet
        ?(Y/N) ');
    Read(Kbd,Ch); ClrScr;
    If Ch IN ['n','N'] THEN CalculateAngles; ClrScr;
    GotoXY(10,9); Write(' Hit any Key to continue.....');
    Read(Kbd,Ch); ClrScr;
    GotoXY(10,9); Write('You will now see the Thigh angle Vs.
        time graph');
    GotoXY(10,11); Write('being plotted. Note the Number of
        Turning Points. ');
    GotoXY(10,13); Write('(i.e, the number of "Hills" and
        "Valleys" on the graph)');
    GotoXY(10,17); Write('Hit any key to continue.....');
    Read(Kbd,Ch); ClrScr;
    PlotThighVsTime;
    ClrScr;
    assign(input, '');
    reset(input);
    GotoXY(10,9); Write('Enter Number of Turning Points  :  ');
    Read(NumberTurningPoints); ClrScr;
    EstCyclePeriod:=Round(2*NumberFrames/NumberTurningPoints);
    IF EstCyclePeriod <= NumberFrames THEN BEGIN
        Offset:=3;
        IF EstCyclePeriod=NumberFrames THEN OffSet:=6;
        For LoopCntr:=1 to 5 DO BEGIN
            Sum[LoopCntr]:=0;Frame:=0;CPCntr:=0;
            While CPCntr <= NumberFrames DO BEGIN
                Frame:=Frame+1;
                CpCntr:=Frame+EstCyclePeriod+LoopCntr-Offset;
                Sum[LoopCntr]:=Sum[LoopCntr]+Abs(ThighAngle[Frame]-
                    ThighAngle[CpCntr]);
            END; {Of While}
        END;
    END;

```

```

Sum[LoopCntr]:=Sum[LoopCntr]/Frame;
END; {Of FOR Loop}
MinCntr:=1;Min:=Sum[1];
For LoopCntr:= 2 to 5 DO BEGIN
IF Sum[LoopCntr]<Min THEN BEGIN
MinCntr:=LoopCntr;
Min:=Sum[LoopCntr];
END; {Of IF loop}
END;
CyclePeriod:=EstCyclePeriod+MinCntr-Offset;
CycleTime:=CyclePeriod*(Send_Time+Expose_Time)/1000;
Cadence:=120/CycleTime;
{Now the Stride Length is calculated}
LoopCntr:=0;Frame:=0;StrideLength:=0;NextFrame:=0;
WHILE NextFrame <= NumberFrames DO BEGIN
Frame:=Frame+1;
NextFrame:=Frame+CyclePeriod;
LoopCntr:=LoopCntr+1;
StrideLength:=StrideLength+ABS(Xcoord[3,Frame]-
Xcoord[3,NextFrame]);
END; {OF WHILE}
StrideLength:=0.001*StrideLength/LoopCntr;
AverageSpeed:=StrideLength/CycleTime;
GotoXY(25,3); Write('TEMPORAL DATA');
GotoXY(22,6); Write('SUBJECT   : ',Subject);
GotoXY(22,8); Write('DATE     : ',Date);
GotoXY(22,10); Write('COMMENTS : ',Comment);
GotoXY(20,14); Write('Cycle Time = ',CycleTime:3:2,' Seconds');

GotoXY(20,16); Write('Cadence   = ',Cadence:4:0,' Steps/Min');

GotoXY(20,18); Write('Stride Length = ',StrideLength:3:2,'
metres');
GotoXY(20,20); Write('Average Speed   = ',AverageSpeed:3:2,'
m/s');
GotoXY(20,24); Write('Hit any key to continue.....');
Read(Kbd,Ch);
END {Of big IF loop}
ELSE BEGIN
ClrScr;
GotoXY(10,10);Write('It would appear that you have less than');
GotoXY(10,12);Write('one gait cycle of data. The temporal data');
GotoXY(10,14);Write('therefore cannot be calculated. ');
GotoXY(12,18);Write('Hit any key to continue.....');Read(Kbd,Ch);
END; {of Else}
END; {Of Procedure TemporalData}

```

```
{*****}
```

```
PROCEDURE RangeOfMotion;
```

```
{This subprogram calculates the ranges of motion of the knee and thigh as well as the mid point ranges}
```

```

BEGIN
ClrScr;
GotoXY(10,5); Write('The Knee and thigh Ranges of Motion may');
GotoXY(10,7); Write('be calculated from the following graph. ');
GotoXY(10,9); Write('Have you calculated the Angle data yet ?
(Y/N)');
Read(Kbd,Ch);ClrScr;
IF Ch IN ['n','N'] THEN CalculateAngles; ClrScr;
GotoXY(10,9); Write ('Hit any key to continue.....');
Read(Kbd,Ch); ClrScr;
PlotKneeVsThigh;
Assign(input,'');
reset(input);
ClrScr;
KneeROM:=MaxKneeAngle-MinKneeAngle;

```

```

ThighROM:=MaxThighAngle-MinThighAngle;
KneeMidPt:=ABS(KneeROM/2+MinKneeAngle);
ThighMidPt:=(ThighROM/2+MinThighAngle);
GotoXY(21,3); Write( 'RANGE OF MOTION DATA');
GotoXY(20,6); Write(Subject);
GotoXY(20,8); Write(Date);
GotoXY(20,10); Write(Comment);
GotoXY(20,14); Write('Knee Range of Motion = ',KneeROM:3:1,'
degrees');
GotoXY(20,16); Write('Thigh Range of Motion = ',ThighROM:3:1,'
degrees');
GotoXY(20,18); Write('Knee MidPoint Value = ',KneeMidPt:3:1,'
degrees');
GotoXY(20,20); Write('Thigh MidPoint Value = ',ThighMidPt:3:1,'
degrees');
GotoXY(24,22); Write('Hit any key to continue.....');

Read(Kbd,Ch); ClrScr;
END; {Of procedure RangeOfMotion}

```

```
{*****}
```

```
PROCEDURE AreaPerimeter;
```

```
{This program outputs the area and perimeter of the polygon enclosed
by the Knee Angle Vs. Thigh Angle diagram}
```

```
VAR
```

```

Sum                               : array[1..5] of Real;
NumberTurningPoints,
Min, CycleTime, APRatio,
CTime, cpd                         : Real;
EstCyclePeriod,
ECyclePeriod, CPeriod,
Offset, CyclePeriod,
LoopCntr, CpCntr,
MinCntr, NFrames                   : Integer;

```

```
BEGIN
```

```

ClrScr;
GotoXY(10,5); Write('The Area and Perimeter may be calculated');
GotoXY(10,7); Write('from the Knee Vs. Thigh Angle Graph. ');
GotoXY(10,9); Write('Have You calculated the angle data yet ?
(Y/N)');
Read(Kbd,Ch); ClrScr;
If Ch IN ['n', 'N'] THEN CalculateAngles; ClrScr;
GotoXY(10,9); Write(' Hit any Key to continue.....');
Read(Kbd,Ch); ClrScr;
PlotKneeVsThigh;
ClrScr;
GotoXY(10,9); Write('You will now see the Thigh angle Vs.
time graph');
GotoXY(10,11); Write('being plotted. Note the Number of
Turning Points. ');
GotoXY(10,13); Write('(i.e, the number of "Hills" and
"Valleys" on the graph)');
GotoXY(10,17); Write('Hit any key to continue.....');
Read(Kbd,Ch); ClrScr;
PlotThighVsTime;
ClrScr;
assign(input, '');
reset(input);
GotoXY(10,9); Write('Enter Number of Turning Points : ');
Read(NumberTurningPoints); ClrScr;
EstCyclePeriod:=Round(2*NumberFrames/NumberTurningPoints);
IF EstCyclePeriod <= NumberFrames THEN BEGIN
Offset:=3;

```

```

        IF EstCyclePeriod=NumberFrames THEN Offset:=6;
        For LoopCntr:=1 to 5 DO BEGIN
            Sum[LoopCntr]:=0;Frame:=0;CPCntr:=0;
            Frame:=Frame+1;
            CpCntr:=Frame+EstCyclePeriod+LoopCntr-Offset;
            Sum[LoopCntr]:=Sum[LoopCntr]+Abs(ThighAngle[Frame]-
ThighAngle[CpCntr]);
            END; {Of While}
        Sum[LoopCntr]:=Sum[LoopCntr]/Frame;
        END; {Of FOR Loop}
        MinCntr:=1;Min:=Sum[1];
        For LoopCntr:= 2 to 5 DO BEGIN
            IF Sum[LoopCntr]<Min THEN BEGIN
                MinCntr:=LoopCntr;
                Min:=Sum[LoopCntr];
            END; {Of IF loop}
        END;
        CyclePeriod:=EstCyclePeriod+MinCntr-Offset;
        CycleTime:=CyclePeriod*(Send_Time+Expose_Time)/1000;
        CTime:=CycleTime;
        Cperiod:=Round((Ctime)*1000/(Send_Time+Expose_Time));
        EcyclePeriod:=CPeriod;
        NFrames:=round(EcyclePeriod);
        Areal:=0;
        ThighAngle[NFrames+1]:=ThighAngle[1];
        KneeAngle[NFrames+1]:=KneeAngle[1];
        FOR Frame:=1 TO NFrames DO BEGIN
            Areal:=Areal+(ThighAngle[Frame]-ThighAngle[Frame+1])*
                (KneeAngle[Frame]+KneeAngle[Frame+1]);
        END; {OF Area Frame Loop};

        Periml:=0;
        Perimtr:=0;
        For Frame:=1 to NFrames-1 DO BEGIN

            Perimtr:=Periml+Sqrt(((ThighAngle[Frame+1]-ThighAngle[Frame])*
                (ThighAngle[Frame+1]-ThighAngle[Frame]))+
                ((KneeAngle[Frame+1]-KneeAngle[Frame])*
                (KneeAngle[Frame+1]-KneeAngle[Frame])));
            Periml:=Perimtr;

        END; {OF Perimeter Loop}
        Area:=Abs(Areal)/2;
        Perimeter:=Perimtr;
        APRatio:=(Sqrt(Area)/Perimeter);
        GotoXY(21,3); Write('AREA AND PERIMETER');
        GotoXY(20,6); Write('SUBJECT:      ',Subject);
        GotoXY(20,8); Write('DATE:      ',Date);
        GotoXY(20,10); Write('COMMENT:    ',Comment);
        GotoXY(20,14); Write('AREA (A) = ',area:3:2,'
                Sq.degrees');
        GotoXY(20,16); Write('PERIMETER (P) = ',perimeter:3:2,'
                degrees');
        GotoXY(20,18); Write('RATIO (SQRT(A)/P) = ',APRatio:3:2 );
        GotoXY(24,22); Write('Hit any key to continue.....');
        Read(Kbd,Ch); ClrScr;
        END; {OF Procedure AreaPerimeter}

{*****}

BEGIN {of program DISPLAY}

FrameStart:=1;FrameEnd:=1;
MarkerStart:=1; MarkerEnd:=1;
NumberFrames:=1;NumberMarkers:=1;
assign(input,'');
reset(input);
    WHILE NOT Done DO BEGIN
        assign(input,'');
        reset(input);
    END;

```

```

REPEAT
{
  assign(input, '');}
reset(input);
  ClrScr;
  GotoXY(30, 4);Write('DISPLAY MENU');
  GotoXY(5, 9);Write('(1)  Read Data from Disk');
  GotoXY(5, 11);Write('(2)  Plot Raw Data');
  GotoXY(5, 13);Write('(3)  Plot StickFigures');
  GotoXY(5, 15);Write('(4)  Plot Trajectories');
  GotoXY(5, 17);Write('(5)  Write Angles to Disk');
  GotoXY(45, 9);Write('(6)  Plot Angles');
  GotoXY(45,11);Write('(7)  Calculate Temporal Data');
  GotoXY(45,13);Write('(8)  Calculate Area & Perimeter');
  GotoXY(45,15);Write('(9)  Range of Motion');
  GotoXY(45,17);Write('(X)  Exit Program');
  GotoXY(27,21);Write('Enter your choice now');
  Read(Kbd,Ch);Ch:=UpCase(Ch);
UNTIL Ch in Menu;
CASE Ch OF
  '1' : ReadDataFromDisk;
  '2' : PlotRawData;
  '3' : PlotStickFigures;
  '4' : PlotTrajectories;
  '5' : WriteAnglestoDisk;
  '6' : PlotAngles;
  '7' : TemporalData;
  '8' : AreaPerimeter;
  '9' : RangeOfMotion;
  'X' : Done:=True;
  END; {of case}
END; {of while}
Done:=False;
ClrScr;
Close(input);
CloseGraph;
Close(output);
END.
{of program DISPLAY}

```

Appendix F
Temporal Calculations

TEMPORAL CALCULATIONS

In order to verify the frame rate of the camera system used, it was necessary to perform a temporal test before commencement of data capture. A marker was dropped from a known distance above the ground while the camera recorded the drop. The sequence was later digitised using the digitising software (which was modified to accommodate the faster rate encountered in dropping the marker). The Y co-ordinates were scaled from pixel units to metric co-ordinates using the scaling factor. The data was then imported into STATISTICA (StatSoft, Inc, Oklahoma, USA) and a curve fitting equation derived for a second order polynomial as depicted in Figure F.1.

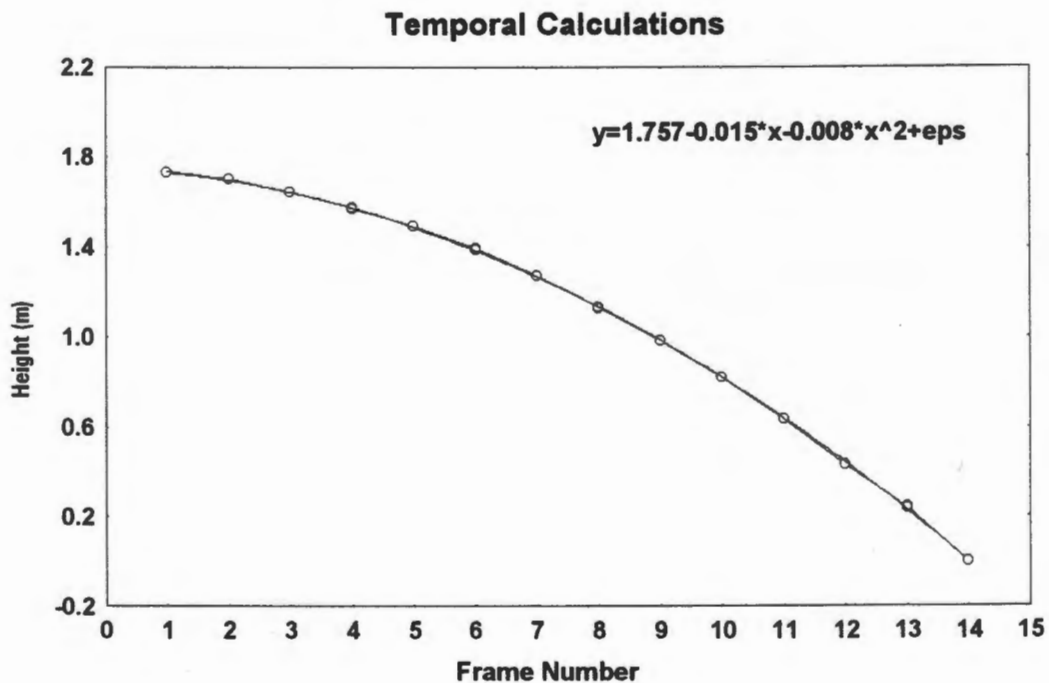


Figure F.1 Graph of raw displacement for falling marker measured in metres above ground level.

Using the equation

$$y = y_0 + ut - \frac{1}{2}gt^2 \quad (\text{F.1})$$

Where y_0 = initial drop height in metres

u = initial velocity in m/s

g = acceleration due to gravity in m/s^2

t = time in seconds

The regression equation fitted into the data is

$$y = 1.757 - 0.015x - 0.008x^2 \quad (\text{F.2})$$

Where y_0 = 1.757 m

x = frame number

-0.015 = initial velocity in metres/frame

From the equation obtained from Figure F.1, and equating co-efficients from equations F.1 and F.2, we get,

$$-0.008x^2 = -4.9t^2 \quad (\text{F.3})$$

from which we get the frame rate as

$$x = 24.74 \cong 25 \text{ frames per second.} \quad (\text{F.4})$$

The regression equation obtained from Statistica only provided 3 significant digits for the coefficients and this in turn decreased the accuracy in the calculation of the frame rate value.

The temporal data obtained for each of the camera systems were digitised and each set yielded a result of 25 frames per second thus verifying the assumption that the frame rate for the VCR system conformed to the PAL system specifications used in South Africa.

Appendix G

Values of left and right side gait parameters

obtained for the ten year study

LEFT SIDE GAIT

Subject	KROM (deg)	TROM (deg)	KMRV (deg)	TMRV (deg)	Cadence (Steps/min)	Stride Length (m)	Average Velocity (m/s)	Arca (sq. deg)	Perimeter (deg)	Ratio
AB	37	33	28	2	38	0.40	0.13	464.41	106.00	0.21
AC	53	42	41	14	85	1.16	0.82	1105.90	154.10	0.22
SC	31	38	33	16	92	0.89	0.68	478.87	113.08	0.20
MJ	54	46	30	3	100	1.24	1.03	1276.01	176.31	0.20
PL	51	32	29	7	100	0.74	0.61	614.50	150.36	0.20
NM	45	49	46	19	76	0.88	0.56	783.59	118.97	0.24
BP	58	56	29	3	95	1.26	1.00	1814.26	175.01	0.24
LR	53	50	46	22	93	0.69	0.53	1247.71	161.25	0.22
FS	55	49	44	10	140	1.16	1.35	1327.00	151.93	0.24
OW	56	35	36	5	88	1.03	0.75	1049.29	145.74	0.22
MW	64	47	50	15	103	1.28	1.11	1646.28	192.20	0.21
Average	51	43	38	10	92	0.98	0.78	1073.44	149.54	0.22
S.D.	9	8	8	7	24	0.28	0.33	450.93	27.43	0.02

Table G.1 Values of left side gait parameters (in standard units) obtained for the subjects in the ten year study.

RIGHT SIDE GAIT

Subject	KROM (deg)	TROM (deg)	KMRV (deg)	TMRV (deg)	Cadence (Steps/min)	Stride Length (m)	Average Velocity (m/s)	Area (sq. deg)	Perimeter (deg)	Ratio
AB	9	27	15	-2	35	0.41	0.12	23.79	76.07	0.06
AC	48	37	42	15	93	1.18	0.91	922.16	123.77	0.25
SC	54	37	36	10	98	0.77	0.63	1183.74	163.63	0.22
MJ	58	46	35	4	102	1.30	1.10	1505.71	174.77	0.23
PL	48	39	24	6	100	0.82	0.69	772.40	133.35	0.21
NM	72	63	54	21	38	0.88	0.28	1315.73	253.31	0.14
BP	57	51	30	4	92	1.26	0.96	1362.00	162.00	0.23
LR	65	54	38	17	93	0.66	0.51	1061.38	143.06	0.23
FS	56	49	31	0	124	1.30	1.33	1336.91	174.57	0.21
OW	64	49	38	7	85	1.12	0.79	1602.91	161.95	0.25
MW	49	52	43	11	113	1.21	1.14	1187.05	153.28	0.23
Average	53	46	35	8	88	0.99	0.77	1115.80	156.34	0.21
S. D.	16	10	10	7	28	0.30	0.37	435.81	42.91	0.06

Table G.2 Values of right side gait parameters (in standard units) obtained for the subjects in the ten year study.

LEFT SIDE SPATIAL-TEMPORAL PARAMETERS

Subject	Leg Length (m)	Froude Number	sqrt(g/lo)	Cadence	Stride Length	Average Velocity
AB	0.7	2.62	3.74	0.17	0.57	0.05
AC	0.89	2.95	3.32	0.43	1.30	0.28
SC	0.76	2.73	3.59	0.43	1.17	0.25
MJ	0.96	3.07	3.20	0.52	1.29	0.34
PL	0.84	2.87	3.42	0.49	0.88	0.21
NM	0.65	2.52	3.88	0.33	1.35	0.22
BP	0.86	2.90	3.38	0.47	1.47	0.34
LR	0.74	2.69	3.64	0.43	0.93	0.2
FS	0.8	2.80	3.50	0.67	1.45	0.48
OW	0.99	3.11	3.15	0.47	1.04	0.24
MW	0.79	2.78	3.52	0.49	1.62	0.40
Average	0.82	2.82	3.48	0.45	1.19	0.27
S. D.	0.10	0.18	0.22	0.12	0.31	0.11

Table G.3 Leg lengths (in metres), the Froude number, and other left side spatial - temporal parameters in dimensionless units obtained for the ten year study.

RIGHT SIDE SPATIAL-TEMPORAL PARAMETERS

Subject	Leg Length (m)	Froude Number	sqrt(g/lo)	Cadence	Stride Length	Average Velocity
AB	0.7	2.62	3.74	0.16	0.59	0.05
AC	0.89	2.95	3.32	0.47	1.33	0.31
SC	0.76	2.73	3.59	0.45	1.01	0.23
MJ	0.96	3.07	3.20	0.53	1.35	0.36
PL	0.84	2.87	3.42	0.49	0.98	0.24
NM	0.65	2.52	3.88	0.16	1.35	0.11
BP	0.86	2.90	3.38	0.45	1.47	0.33
LR	0.74	2.69	3.64	0.43	0.89	0.19
FS	0.8	2.80	3.50	0.59	1.63	0.48
OW	0.99	3.11	3.15	0.45	1.13	0.25
MW	0.79	2.78	3.52	0.53	1.53	0.41
Average	0.82	2.82	3.48	0.43	1.21	0.27
S. D.	0.10	0.18	0.22	0.14	0.31	0.13

Table G.4 Leg lengths (in metres), the Froude number, and other right side spatial - temporal parameters in dimensionless units obtained for the ten year study.

Appendix H

**Values of left and right gait parameters obtained
for the age-matched normal controls**

LEFT SIDE GAIT - NORMAL CONTROLS

Subjects	KROM (deg)	TROM (deg)	KMRV (deg)	TMRV (deg)	Cad (steps/min)	St. Lgth (m)	Av. Vel. (m/s)	AREA (sq. deg)	Pmtr. (deg)	Ratio
AA	60.3	49.0	30.4	-0.3	103	1.33	1.13	1895.14	183.22	0.24
AJ	60.9	41.1	31.3	0.0	121	1.30	1.31	1494.02	176.90	0.22
SB	55.0	37.5	29.2	4.1	126	1.54	1.62	1077.40	164.56	0.20
MG	58.2	38.4	29.9	0.5	102	1.24	1.06	1216.24	163.32	0.21
LK	65.1	51.4	32.9	5.6	104	1.23	1.07	1896.76	179.26	0.24
SK	54.9	41.7	29.0	2.6	110	1.44	1.33	1139.46	173.48	0.20
EL	58.6	37.2	33.4	7.5	117	1.17	1.14	1170.75	157.50	0.22
QL	56.8	41.6	28.5	1.0	121	1.26	1.28	1452.94	170.76	0.22
DR	58.5	37.2	29.7	4.5	111	1.16	1.08	1140.95	157.59	0.22
MT	61.8	41.6	31.2	-0.5	110	1.19	1.10	1575.33	168.52	0.23
BV	59.2	40.1	34.0	5.7	120	1.20	1.20	1416.26	162.05	0.23
GV	54.5	39.3	28.0	-0.8	112	1.27	1.19	1086.83	150.70	0.22
Average	58.6	41.3	30.6	2.5	113	1.28	1.21	1380.17	167.32	0.22
S. D.	3.1	4.5	2.0	2.9	8	0.11	0.16	294.39	9.80	0.01

Table H.1 Values of left side gait parameters (in standard units) obtained for the age-matched normal controls.

RIGHT SIDE GAIT - NORMAL CONTROLS

Subjects	KROM (deg)	TROM (deg)	KMRV (deg)	TMRV (deg)	Cadence (Steps/min)	Stride Length (m)	Average Velocity (m/s)	Area (sq. deg)	Perimeter (deg)	A/P Ratio
AA	65.9	50.2	33.7	6.0	100	1.38	1.15	2136.56	195.35	0.24
AJ	60.7	44.2	39.9	5.6	132	1.22	1.34	1483.07	156.99	0.25
SB	56.8	40.7	30.5	5.0	129	1.60	1.72	1151.06	176.27	0.19
MG	59.7	42.1	31.5	2.3	103	1.28	1.11	1210.71	162.90	0.21
LK	65.9	51.8	34.0	7.3	108	1.19	1.07	2077.65	157.75	0.29
SK	56.7	43.5	34.0	8.1	108	1.44	1.30	1234.92	187.09	0.19
EL	56.8	42.0	30.3	3.4	119	1.16	1.15	1393.58	151.27	0.25
QL	62.2	45.4	32.1	3.1	123	1.32	1.35	1617.87	174.15	0.23
DR	55.7	39.6	29.9	-1.3	113	1.28	1.20	1306.05	161.46	0.23
MT	57.5	39.7	29.4	-1.1	110	1.16	1.07	1271.12	169.02	0.21
BV	53.3	40.3	27.0	-2.9	123	1.16	1.18	1421.01	151.89	0.25
GV	59.3	44.6	32.4	2.3	113	1.31	1.24	1296.51	163.84	0.22
Average	59.2	43.6	32.0	3.2	115	1.29	1.24	1466.67	167.33	0.23
S. D.	3.9	3.9	3.2	3.5	10	0.13	0.18	325.36	13.71	0.03

Table H.2 Values of right side gait parameters (in standard units) obtained for the age-matched normal controls.

**LEFT SIDE SPATIAL-TEMPORAL PARAMETERS
NORMAL-CONTROLS**

	Leg Length (m)	Froude Number	sqrt(g/lo)	Cadence	Stride Length	Average Velocity
AA	0.78	2.76	3.54	0.48	1.70	0.41
AJ	0.76	2.73	3.59	0.56	1.70	0.48
SB	0.88	2.94	3.34	0.63	1.74	0.55
MG	0.82	2.83	3.46	0.49	1.52	0.37
LK	0.78	2.76	3.54	0.49	1.58	0.39
SK	0.87	2.92	3.36	0.55	1.66	0.45
EL	0.76	2.73	3.59	0.54	1.54	0.42
QL	0.79	2.78	3.52	0.57	1.59	0.46
DR	0.87	2.92	3.36	0.55	1.34	0.37
MT	0.87	2.92	3.36	0.55	1.37	0.38
BV	0.86	2.90	3.38	0.59	1.39	0.41
GV	0.78	2.76	3.56	0.52	1.64	0.43
Average	0.82	2.83	3.47	0.54	1.56	0.43
S. D.	0.05	0.08	0.10	0.04	0.14	0.05

Table H.3 Leg lengths (in metres), the Froude number, and other left side spatial-temporal parameters in dimensionless units obtained for the age-matched normal controls.

**RIGHT SIDE SPATIAL-TEMPORAL PARAMETERS
NORMAL CONTROLS**

	Leg Length (m)	Froude Number	sqrt(g/lo)	Cadence	Stride Length	Average Velocity
AA	0.78	2.76	3.54	0.47	1.76	0.42
AJ	0.76	2.73	3.59	0.61	1.6	0.49
SB	0.88	2.94	3.34	0.64	1.81	0.58
MG	0.82	2.83	3.46	0.50	1.56	0.39
LK	0.78	2.76	3.54	0.51	1.53	0.39
SK	0.87	2.92	3.36	0.54	1.65	0.44
EL	0.76	2.73	3.59	0.55	1.52	0.42
QL	0.79	2.78	3.52	0.58	1.67	0.48
DR	0.87	2.92	3.36	0.56	1.47	0.41
MT	0.87	2.92	3.36	0.55	1.33	0.36
BV	0.86	2.90	3.38	0.60	1.35	0.41
GV	0.78	2.76	3.56	0.53	1.69	0.45
Average	0.82	2.83	3.47	0.55	1.58	0.44
S. D.	0.05	0.08	0.10	0.05	0.15	0.06

Table H.4 Leg lengths (in metres), the Froude number, and other right side spatial-temporal parameters in dimensionless units obtained for the age-matched normal controls.

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