IDENTIFYING PRIMARY AND COMPENSATORY ABNORMALITIES USING SINGLE AND DOUBLE LIMB SUPPORT PHASE GAIT ANALYSIS

Dissertation submitted in partial fulfilment of the requirement of The Tamilnadu Dr. M.G.R. Medical University, Chennai for the MD branch XXI (Physical Medicine and Rehabilitation) examination held in May 2011.

Certificate

This is to certify that 'IDENTIFYING PRIMARY AND COMPENSATORY ABNORMALITIES USING SINGLE AND DOUBLE LIMB SUPPORT PHASE GAIT ANALYSIS' is the bonafide work of

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TITLE

IDENTIFYING PRIMARY AND COMPENSATORY ABNORMALITIES USING SINGLE AND DOUBLE LIMB SUPPORT PHASE GAIT ANALYSIS

PLACE OF STUDY

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ABSTRACT

This study describes biomechanical forces on bipedal gait in 2 phases - on both limbs in double limb support (DLS) and while on one limb is in single limb support (SLS) with the opposite limb in swing. Primary abnormalities are muscle activity abnormalities which directly cause abnormalities in gait. Secondary abnormalities are compensatory muscle activities which try and correct primary abnormalities. This study describes kinetic, kinematic and dynamic EMG characteristics of DLS and SLS using 36 gait data cycles from 18 gait collections. DLS/SLS analysis is used to identify primary and secondary abnormalities in gait. The stability function of DLS is commonly affected by knee and ankle power absorption and this is due to a combination of impaired voluntary control at the knee in DLS1 and spasticity at the ankle in DLS2. The primary abnormality in SLS is spasticity but this spasticity might actually be compensatory or beneficial. Swing is characterized by mostly normal kinematic, EMG and kinetic activity. The hip is relatively spared especially with regards to EMG and range of movement. DLS/SLS analysis is a useful tool in diagnosing primary and secondary abnormalities in gait.

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CHAPTER ONE

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INTRODUCTION TO NORMAL GAIT

Gait is defined by Bleck as bipedal plantigrade progression (1) . Alternatively, it has been described as a highly controlled, co-ordinated, repetitive series of limb movements whose function is to advance the body safely from place to place with a minimum expenditure of energy (2).

STUDYING NORMAL GAIT

There are various aspects of walking that have been examined by various researchers over the years. The gait cycle is the easiest, commonest way of looking at walking patterns (2). Stability, smoothness and energy efficiency of gait are also important parameters (3) which have been examined in different ways.

1. GAIT CYCLE:

Walking pattern is studied as a gait cycle which is often defined as initial contact of the foot to successive ipsilateral initial contact. The gait cycle is divided into stance (60%) and swing (40%) phases.

The stance phase is further sub-divided into periods: initial contact (IC), loading response (LR), mid stance (MSt), terminal stance (TSt) and pre-swing (PSw).

The swing phase is divided into three periods (initial (ISw), mid (MSw) and terminal swing (TSw)) respectively (2).

Each phase is defined with various sagittal plane events at the hip, knee and ankle (Sagittal kinematics):

Table 1.1: Hip, knee, ankle and foot movements in sagittal events of gait.

EVENTS	***HIP***	***KNEE***	***ANKLE & FOOT***
STANCE			
Initial Contact	F	E	DF
Loading Response	Begins E	Starts F	Heel rocker
Mid Stance	E to N	E to N	Ankle rocker
Terminal Stance	N to hyperE	Full E	Forefoot rocker
Pre-Swing	Begins F	Starts F	PF
SWING			
Initial Swing	N to F	Rapid F	Starts DF
Mid Swing ***(Vertical Tibia)***	Completing F	Starts E	Ongoing DF
Terminal Swing	Completed F	Still E	To N

Key: F = flexion E = extension DF = dorsiflexion PF = plantarflexion N = neutral

In the past, different terminologies have been used for these phases, periods and events of gait. Stance has been divided into heel strike, foot flat, toe off (4). These have the drawback of not being able to describe abnormal foot patterns e.g. heel strike never occurs in equinus gait. Therefore a more contemporary terminology like initial contact is preferable.

In addition, normal frontal and transverse kinematics have also been described in Table 1.2

Table 1.2: Transverse and Frontal kinematics in gait

	Transverse kinematics	Frontal kinematics
Pelvis	Rotates forward in stance & till end of 1st DLS	Trendelenberg from onset of SLS
Hip	Rotates backward from onset of SLS through 2nd DLS	Elevated in swing and hip internally rotates
	Rotates forward again from ISw and hip ER	Trendelenberg again in ISw
Knee	Tibia rotates around the ankle in SLS	

Key: ISw = initial swing DLS = double limb support SLS = single limb support IR = internal rotation ER = external rotation

2. GAIT STABILITY IN STANCE AND MOBILITY IN SWING

Gait can also be divided based on the functional aspects of stability in stance and mobility in swing. Single limb support (SLS) occurs in the middle of stance as the opposite limb swings. Single limb stance is the working phase of gait - the trunk is propelled past the stance foot. This is around 40% of a stable gait cycle. The remaining 20% is divided equally for the beginning and end of stance and is termed double limb support (DLS). These definitions of gait are used functionally to understand stability (DLS) and mobility (SLS) functions of gait.

Table 1.3: Single and Double limb support phases of gait

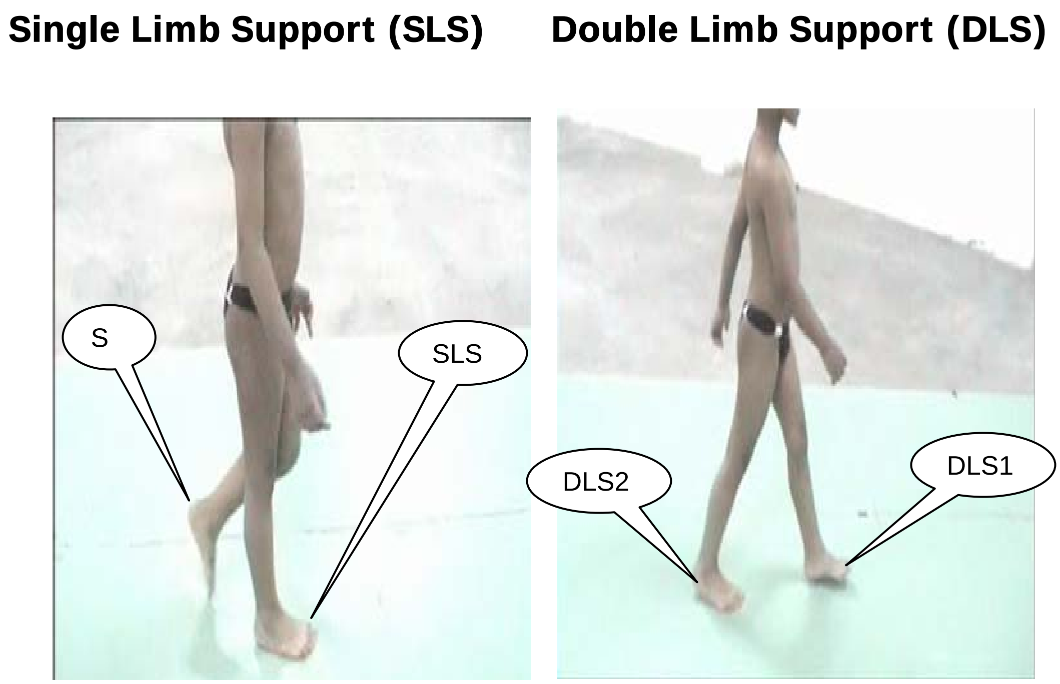
	Initial DLS (DLS1)	SLS	2nd DLS (DLS2)
%	10%	40%	10%
Events	IC,LR	MSt, TSt reversal fore-aft shear	PSw, TO
Contralateral limb events		Contralateral TO & IC @ 50%	

Key: IC = Initial Contact; LR = Loading response; MSt = mid stance; TSt = terminal stance; PSw = pre-swing; TO = toe off

The biomechanical effects of ground reaction forces on walking are also simplified as DLS/SLS not only take into account bilateral events but also focus on the contact on the ground – either through both feet or one. Thus the essence of biomechanical analysis accommodated in this type of gait analysis. This type of analysis is also justified by my previous study showing significant differences in SLS on comparison of normal gait vs. cerebral palsy gait (5).

The comprehensive bilateral components in DLS/SLS phases of gait are easier to correlate because SLS corresponds to contralateral swing and DLS1 corresponds to contralateral DLS2 and vice versa.

Fig 1.1: Single and double limb support phases of gait



AS Macaden, S Bhattacharji, RKR Chilman, T Ganesh, J George, NG Nair. ***What Gait Analysis tells us about clinical examination of spastic gait in children.*** **Indian Journal of PMR October 2005; 16(2): 45-47.**

3. ENERGY EFFICIENCY OR ECONOMY OF TRANSLATION

Energy cost of ambulation is 0.8 calorie/m/kg at comfortable walking speed. The energy cost of gait is measured by the force with which the ground reaction forces act on the contacting limbs. Oxygen consumption is another measure of energy cost of walking. Gait patterns aim at economizing energy. Six determinants of gait were described by Inman in 1953 in one of the first citation classics on gait (6). These determinants were said to be responsible for optimal efficiency of walking. The centre of gravity (CoG), which is just anterior to S1 vertebra, is as minimally displaced as possible like the axle of a wheel.

These determinants are:

1. Pelvic rotation - decreases vertical drop of CoG in stance, increases step length in swing.

2. Pelvic list (Trendelenberg) - decreases vertical rise of CoG in swing.

3. Lateral displacement of pelvis - keeps the body within the base of support.

4. Knee flexion in stance - decreases vertical elevation of body in MSt, absorbs shock of IC.

5. Ankle mechanisms - dorsiflexion & plantarflexion control CoG movement, develop forward propulsion.

6. Head-Arm-Trunk (HAT), Knee, ankle, foot rotations - control CoG movement, develop forward propulsion.

Thus, the gait cycle can be studied either as repetitive limb movements, as a propulsive function of stability and mobility or as a sequence of patterns to move the human body using the least amount of energy.

INTRODUCTION TO GAIT ANALYSIS

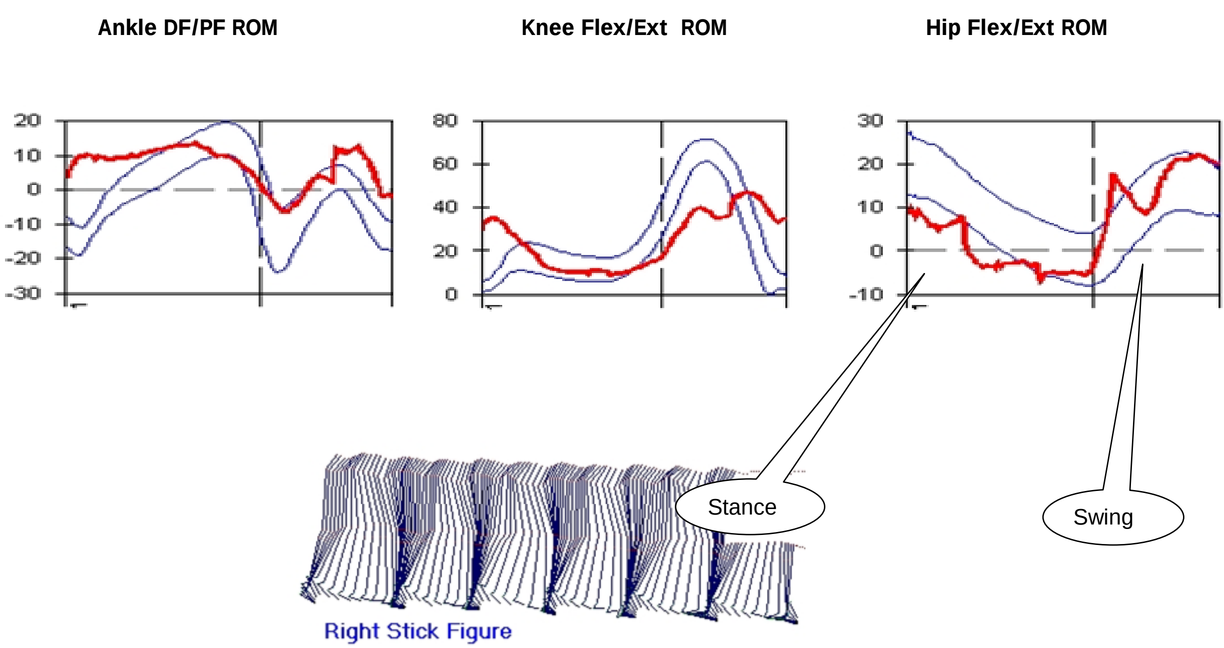
Gait analysis began in 1872 when Edward Muybridge, a noted still photographer of his day, was asked by the governor of California, Leland Stanford, to photograph his running horse with all four feet off the ground. It was several years later that this sequence of photographs could actually be produced by a series of cameras set up on the race track with trip wire switches across the track - the beginning of gait analysis (3). Today gait analysis has progressed far beyond a set of still photographs.

Modern gait analysis systems measures kinematic, kinetic, dynamic electromyographic and energy consumption of gait. A comprehensive system can simultaneously collect all this data required for a complete analysis (7). While this allows far more quantitative analysis by computerised systems, it also produces a vast amount of data:

1. Kinematics describes the spatial movement of the body. It is usually reported in linear or angular displacements, velocities or accelerations in the sagittal, frontal or transverse planes. Kinematic data collected from infrared LEDs, reflectors, telemetric transmitters or electrogoniometers placed on the

patients' body. Using Trigonometry, joint angles can be calculated from Cartesian co-ordinates of the bony prominences in the required plane (8).

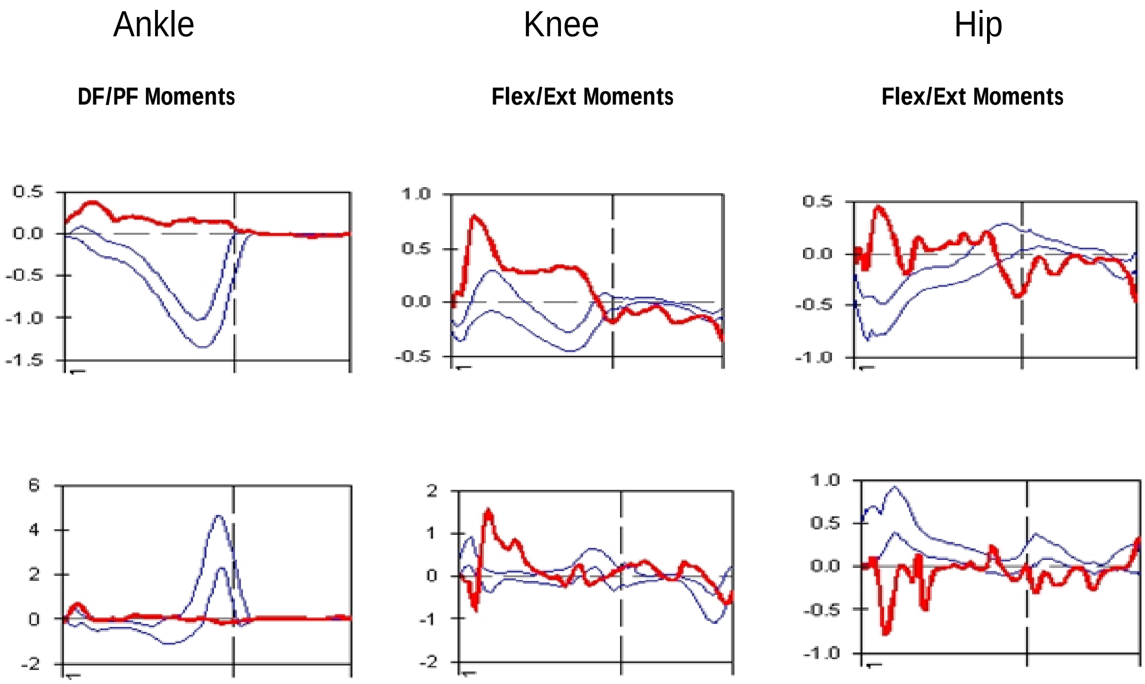
Fig 1.2: Kinematic data – joint ranges and stick figures



Key:
Blue: Normal data; Red: Patient data; DF/PF = Dorsiflexion/Plantarflexion; Flex/Ext = Flexion/Extension.
Notation for y axis in all graphs: variable above 0 / variable below 0

2. Kinetics describe the forces that produce gait. It is usually reported in ground reaction forces (GRF), joint moments and joint powers. Kinetic data is collected when the patient steps on a force plate - the force plate measures the forces of the foot exerted on it. This raw data is then related to kinematic data (acceleration), moments of inertia and to estimated limb segment mass to compute power data (9).

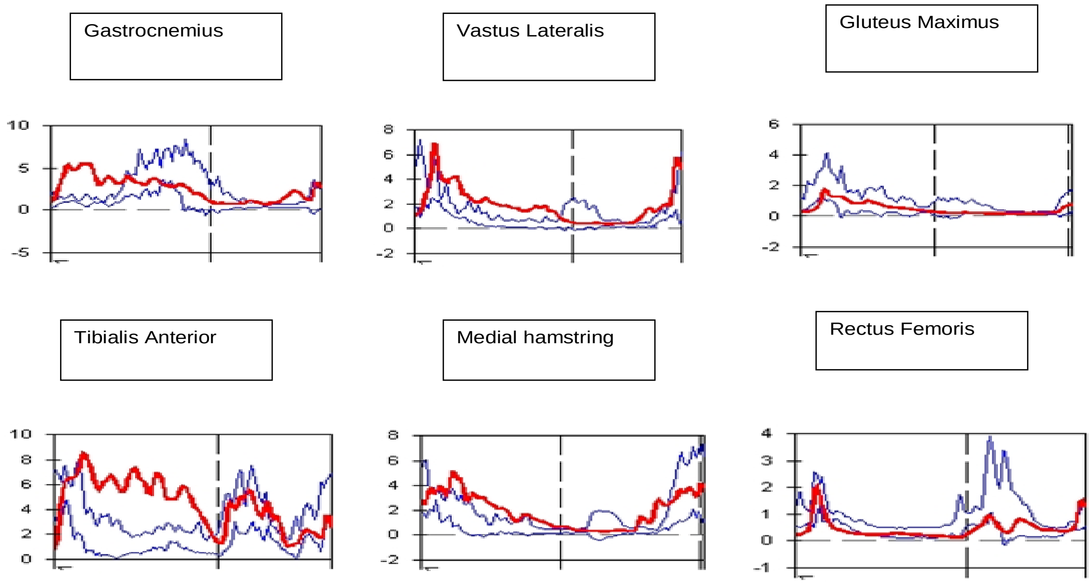
Fig 1.3: Kinetic data



Key: Blue: Normal data; Red: Patient data; DF/PF = Dorsiflexion/Plantarflexion; Flex/Ext = Flexion/Extension; Gen/Abs = generation/absorption.

3. Dynamic Electromyographic (EMG) data describes muscular contractions during each phase of the gait cycle. Dynamic EMG data is collected from surface or needle electrodes over selected muscles combined with footswitches or kinematics to enable definition of the stages of the gait cycle (9-11).

Fig 1.4: Dynamic EMG data



Key: Blue: Normal data; Red: Patient data.

4. Energy consumption data describes energy consumed during gait. This can be measured directly by measuring oxygen consumption or carbon dioxide production over a long period or indirectly by segmental analysis, inverse dynamics (measured as power generation/absorption at each joint – see Fig 1.3) or physiological cost index calculations (12, 13).

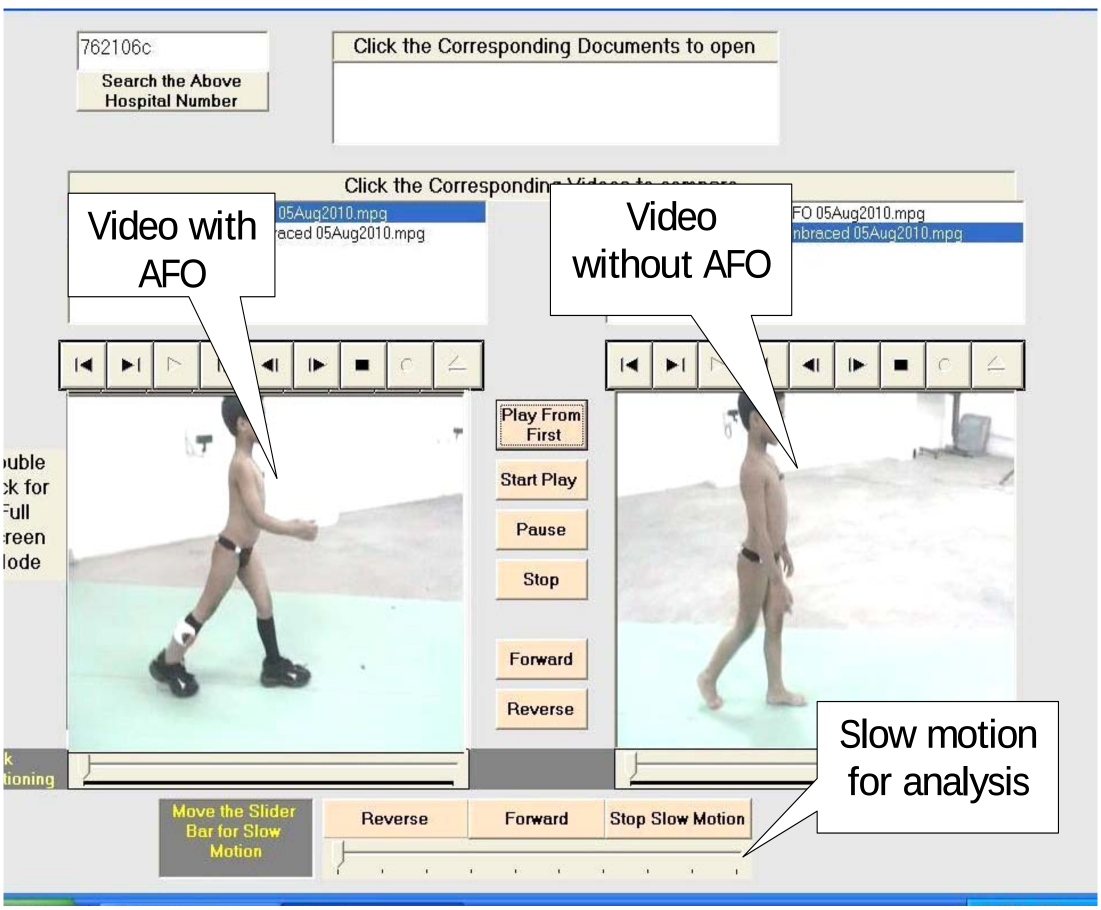
Walking speed and heart rate are combined to produce a Physiological Cost Index (PCI). The PCI is an index of energy consumption rather than an indirect measurement. It is based on the fact that, at sub-maximal heart rates, oxygen consumption and heart rates are linearly related (14).

PCI = (Post exercise HR - resting HR) / average walking speed in meters/min

The advantage of an easily applicable apparatus and good repeatability, make the PCI a good test for energy consumption. Also PCI does not change with age or height and this makes it a good test for follow up of growing children (15). PCI is usually reported as beats per meter.

5. Observational Gait Analysis is a qualitative aid to instrumented gait analysis. Direct observation of gait is difficult and tedious for the person who may have to walk for a long time and cannot be the sole method of analysis of difficult gait (16). On the other hand, ***slow motion*** video gait recordings of antero-posterior and right and left lateral views of gait are a dependable and reproducible method of documenting and analysing gait (11). The Rancho Los Amigos Medical Centre has developed a good format for observational gait analysis which lists deviations from normal in each phase of gait from the trunk down to toes in order (17).

Fig 1.5: Observational gait analysis display software



USES OF GAIT ANALYSIS

Gait analysis, as mentioned above, has been used in cerebral palsy as a preoperative assessment tool and for postoperative evaluation. The other uses of gait analysis are in comparative studies of prostheses(18), orthoses (19) or joint replacement s(20) or to assess progression in neuromuscular disease (21).

INTRODUCTION TO PRIMARY AND SECONDARY GAIT ABNORMALITIES

When gait abnormalities occur as a result of complex and multi-axes neurological or muscular disease involving HAT, pelvis and lower limbs, there are abnormalities which occur directly as a result of the disease which are called primary abnormalities. In addition, the body tries to compensate by shifting biomechanical and kinesiological functions to improve energy efficiency and these appear as abnormalities as well, known as secondary or coping gait abnormalities (7). Though they are seen in Muscular Dystrophy, Polio, Hemiplegic strokes and other neurological or muscular diseases, primary and secondary gait abnormalities have been commonly described in Cerebral Palsy e.g. circumduction of the hip to accommodate a stiff knee in swing caused by co-contracting quadriceps and hamstrings in swing.

It is important to differentiate secondary abnormalities in gait because if these coping responses are corrected, the energy cost of gait will increase and walking might look better but actually be less functional and more difficult. Children may even go off their feet after surgical interventions if secondary abnormalities are corrected without addressing primary abnormalities. On the other hand, correcting primary abnormalities may automatically restore normalcy as no coping responses are needed anymore e.g. restoring knee flexion in swing in the above example will obviate the need for circumduction at the hip (7). There are advantages of identifying primary and secondary abnormalities especially in the management of

Cerebral Palsy - outcomes can be radically changed by gait analysis. It has been said that a careful pre operative analysis of the gait of patients with cerebral palsy has resulted in better long term post operative results (22). With gait analysis it is becoming possible to identify, separate and plan treatment for primary and secondary patterns of gait. With the advent of clinical gait analysis the treatment of gait abnormalities has been transformed from an art to a science (3).

SUMMARY OF INTRODUCTION

Gait is a cycle of movements as a result of forces caused by muscle activity. The forward movement of the body is made energy efficient by improving stability in stance and mobility in swing. Though gait can be described as unilateral changes of each limb, the examination of gait in twinned time phases enables a more appropriate understanding of the ground reaction forces on both limbs the body. These two twinned time phases of gait are:

- single limb support and swing
- first and second double limb supports

These sets of events in time are influenced in pathological gait by multiple factors. It is important to differentiate factors directly caused by disease (primary abnormalities) from those which occur in order to cope with the primary problem (secondary or coping abnormalities). Identifying and removing primary factors in gait can improve even secondary abnormalities. Removing secondary or coping abnormalities can worsen gait. Thus gait analysis needs to identify these primary and secondary gait abnormalities in single and double limb supports.

CHAPTER TWO

REVIEW OF LITERATURE

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INTRODUCTION

Traditional gait analysis is usually based on sagittal plane abnormalities in stance and swing. Gait analysis based on single and double limb support analysis is relatively uncommon. However there are many researchers, including those from our gait lab, who have pointed to usefulness of single limb support in analysing cerebral palsy, amputee, stroke and muscular dystrophy gait abnormalities (5, 23-28). Similarly the importance of being able to identify primary and secondary (coping) abnormalities in gait was first described in 1993 by Gage in cerebral palsy gait (3) .

The research around these two themes are presented in this chapter after discussing the evolution of the traditional stance-swing gait analysis and critique of its practice and development.

CRITIQUE OF TRADITIONAL GAIT ANALYSIS STUDIES

The first published and often quoted study on gait came, as did many subsequent papers, from the University of California, San Francisco in 1953 when Vernon Inman studied and described normal gait (6). Like many studies subsequently, it was the result of the co-ordinated efforts of physicians and engineers (29). Till the late sixties published data on gait analysis were uncommon. David Sutherland described dynamic EMG gait analysis in spastic children (16). It was only in the late seventies that kinesiology laboratories published data on kinematic and kinetic gait analysis in Cerebral Palsy (4, 10, 11). In the last two decades of twentieth century, Gage, Perry, Deluca and others used gait analysis as a pre operative evaluation tool in Cerebral Palsy and described the importance of gait analysis in Cerebral Palsy and other disorders (2, 7, 22).

As studies were published, it was noted that there was a large portion of data that did not show statistical significance between normal and pathological gait, or between different types of pathological gait or between pre and post intervention (23, 30-32). This was surprising especially as in one set of twin studies using gait analysis to assess strengthening, the same subjects who showed no statistically significant differences in gait data, reported symptomatic improvement or showed improvement in functional scores relating to walking (33, 34). Reviews by expert then raised strong voices of discontent and questioned the validity of gait analysis (35). Finally, in 1998, the US department of Veteran’s Affairs published an online monograph in which Gitter and McAnelly described the limitations and unanswered questions facing the gait analysis research community (36). Their summary table (Table no 2.1) is shown.

Table 2.1: Limitations of gait analysis (36)

	Limitations concerning the use of clinical instrumented gait analysis by the physiatrist.	Barriers, Unanswered questions
1	**Lack of objective data that instrumented gait analysis improves patient function.**	• Effect of gait analysis on diagnosis, clinical decision making, and treatment selection is unclear • Lack of cost-effectiveness information
2	**Limited information or guidelines for selecting and applying specific gait analysis techniques in evaluating and treating different gait abnormalities.**	• Is standardization of gait analysis protocols for different disorders useful? • Better definition of the patient populations and gait problems that are benefited by instrumented gait analysis. • Does instrumented "motion" analysis improve the care of non-ambulatory mobility problems or upper limb motor disability?
3	**Limited treatment options for use in the management of adult gait disorders.**	• Current physiatric interventions are empirically based and have low morbidity, lessening the need for instrumented gait analysis. • Improved neuromuscular and musculoskeletal models of gait needed to allow prediction of compensatory strategies and treatment outcomes.
4	**Limited understanding by clinicians of the data generated by instrumented gait analysis.**	• Better training of residents and clinicians in the complexities of the kinematic, kinetic, and motor control features of gait • Improved gait educational media • Standardization of terminology to improve communication

These enigmatic situations (looking for a needle in a haystack) were dealt with in several ways:

1. **The needle is too small**: Inadequate power of the studies due to small numbers of subjects (33). The inappropriate inclusion of diagnostic or pathological criteria rather than gait criteria has resulted in most studies being small in number. Some researchers have overcome this by including data based on biomechanical criteria but other limitations mentioned below have still caused methodological difficulties (37).

2. **Looking for the wrong needle**:

   The wrong choice of kinematic outcome measures: If one chose the maximum range of flexion at the knee in stance as an outcome measure, there might not be a statistical difference in the range of a normal person who flexes to 20 degrees in loading response or pre-swing and a child with crouch gait whose knee remains flexed at 20 degrees through SLS. Studies which have chosen broad kinematic measures have faced this problem (38).

   The wrong choice of dimension: There are quite a few transverse plane abnormalities which may be missed if only sagittal plane analysis is undertaken e.g. femoral neck valgus causes Gluteus Medius to have a poor lever arm causing impaired hip extension in single limb support (39). Indeed, the prominence of transverse plane abnormalities (rather than sagittal plane) in the hip, knee and ankle have been reported (40). Newer methods of gait analysis like the Principal Component Analysis technique which attempts to classify gait patterns using statistical clusters of a combination of gait data, strength scores, spasticity scores, voluntary control and static range of motion, are often still based on sagittal plane abnormalities (37).

3. **Looking in the wrong haystack**:

The wrong choice of temporal outcome measures: Stance phase is a very broad term including periods of time which are biomechanically and functionally very diverse - one lever on the ground in SLS allowing mobility, two levers contacting the ground in DLS providing stability. Gait analysis of stance which does not separate out the events occurring in each of these times, will result in a meaningless set of numbers or a wrong interpretation of data. Several studies which look at these broad temporal data have, not surprisingly, not shown statistically detectable differences (22, 30).

The wrong choice of side: When an abnormality is noted in a joint, the search for a cause is around or in that joint - e. g. a flexed knee in double limb support could be a knee contracture, a weak quadriceps, a spastic hamstring or a flexed hip or dorsiflexed ankle. There are several instances of this not being so. Studies have shown that muscle action on remote joints need to be considered (26). Scott Delp, from the department of Bioengineering, Stanford University, CA, and others have created a freely available biomechanical simulation package called OpenSIM (41) which has been used widely in the twenty first century to identify remote muscle actions on joints (42-45). This mathematical model interacts with gait data and simulates changes. However, most simulations are studied in single limb support. Other results from our simulation-based analyses of walking "*are more surprising. For example, .. that hamstrings weakly accelerate the knee toward extension during stance was unexpected*" (46). This unexpected result may be because the model only looks to the same limb for answers. Researchers have recognized this and propose that "*future studies* *examining double support would provide valuable information about propulsion and the transition from stance to swing"* (42).

Thus, the difficulties in gait analysis could be addressed by looking at coordinated biomechanical information from both sides of the body in very specific periods of time which correlate with the specifically required functions. The next section describes how specific periods of time and specific functional requirements in gait are being studied.

STUDYING SPECIFIC TIMES IN GAIT ANALYSIS (SLS/DLS)

The question of which are the relevant specific times and functions in gait can be answered by a review of literature of the statistically significant findings among the sea of gait data which shows no statistical difference. This is relatively easy as most papers report significant differences.

The first most important global finding in gait analysis is the importance of energy efficiency. The overarching goal of all biomechanical events is to conserve energy. Whether directly measured or indirectly inferred using the Physiological cost index and power generation / absorption data, this variable has always differentiated between normal and abnormal gait patterns (2, 23, 47, 48) Previous research on comparison of the gait of 32 children with Cerebral Palsy and 20 normal gait collections has shown that parameters relating to single limb support are affected i.e. stride length, maximum knee extension in stance, walking speed and lateral ground reaction forces (5). Similar findings emphasizing single limb support and double limb support have been reported in other cerebral palsy studies (24, 25) as well as studies on stroke (28, 49) and amputation (27). Thus the importance of single and double limb support phases are one set of variables to specifically concentrate on in gait analysis. These must be analysed in appropriate time frames. As outlined in the first chapter, one side single limb support occurs at the same time as opposite swing making all the muscles acting in these two phases a set of force couples acting to conserve energy while maintaining mobility. Similarly, both double limb support phases occur at the same time i.e. the right and left at one time period and the left and right at another time period. Again, the muscles involved in these two phase sets act in a set of force couples to conserve energy while providing stability (2). Gage, Deluca and Renshaw proposed that there are eight principles of abnormal gait which govern these events:

1. All gait deviations fall under three headings those caused by
    a. Weakness
    b. Abnormal joint position
    c. Muscle contracture
2. Contractures are either static (acting through the entire gait cycle) or dynamic (acting only in a particular time of the gait cycle).
3. Muscles work as part of a force couple on a bony lever and generate or absorb force on a joint or joints.
4. Inadequate moments on a joint may be due to
    a. Muscle weakness
    b. Deficient mal-directed lever arm (lever arm dysfunction) e.g. internally rotated foot
5. Gait deformities are rarely isolated. They are usually 3 basic types of abnormalities
    a. Primary abnormalities e.g. spasticity
    b. Secondary abnormalities e.g. contractures or torsional bone deformities
    c. Coping responses e.g. vaulting to clear a swinging limb with a stiff knee.

6. Stance phase abnormalities are usually because of abnormal joint position and swing phase abnormalities are usually because of abnormal position as well as inadequate ranges of motion.
7. Selective motor control deficiencies increase from proximal to distal (“proximal compensations for distal deviations”)
8. Bi-articular (two-joint) muscles are more badly affected than single joint muscles because they need a greater level of control to manage two joints (2).

Thus energy conservation, single limb and double support phases, primary and secondary or coping responses are the key variables to be studied and interpreted in greater detail.

STUDYING SPECIFIC FUNCTIONS OF GAIT

Most of the current research into the above mentioned variables use mathematical modelling software to test primary muscle hypotheses and measure the interaction between timing of muscle activity and generation or absorption of moments and powers.

One of the earlier studies in this decade identified the dorsiflexors, Glutei, Vasti and Gastrocsoleus as the main resistors to the downward force of gravity. Before foot flat, the dorsiflexors are the important contributors. At foot flat, there is a transition to hip extensor/abductors and knee extensors. However hamstrings also have the potential to contribute prior to foot flat and can thus compensate weak dorsiflexors. Finally, in late stance, the plantarflexors were the main contributors. Adductors, Erector spinae and iliopsoas developed forces but did not contribute much to support. It is also possible that the contralateral plantarflexors contributed to the forces attributed to the dorsiflexor support before foot flat (46).

Another study agreed with this but found, with advanced modelling, that indirect action of muscles on remote joints needed to be considered in analysis e.g. stance knee extension was required to achieve stance hip extension, the overall magnitude of swing hip flexion by flexors is actually controlled by hip extensors (26).

A stiff knee model looked at knee flexion velocity based on the observation that stiff knee gait in Cerebral palsy was characterised by low knee flexion velocity at toe off. Iliopsoas and Gastrocnemius were identified as the muscles contributing most to increasing knee flexion velocity in DLS. Vastus, Rectus and Soleus did the opposite. Though Sartorius and Gracilis had the largest potential to increase knee flexion velocity, they did not do so in the model. Effects of surgical interventions were also tested in this model. Transferred Rectus Femoris did not generate a knee flexion moment in the model. Rather, distal Rectus Femoris transfer may work by decreasing knee extension moment. Similarly, multiple soft tissue release surgeries of Psoas, Gracilis and hamstrings compromise knee flexion velocity in DLS explaining why post operative side effects of stiff knee gait might occur. Finally Gastrocnemius and Soleus have opposing effects on knee flexion velocity. This implies that surgical interventions should not be done for both together (43).

An equinus foot model showed that it caused knee hyperextension which could be countered by stronger Gastrocnemius (which helps flex knee unlike Soleus) and Vasti. While a traditional ankle foot orthosis solution would be acceptable, lengthening of Tendo Achilles would weaken Gastrocnemius and thus be counterproductive as well as reducing plantarflexor force in late stance (44).

A crouched gait SLS mathematical modelling study showed that Glutei, Vasti and Soleus showed reduced extension capacity with increasing crouch even if activation and physiological strength of these muscles were normal. What did reduce extension capacity was excessive tibial torsion. Surprisingly, for some patients, extended hamstring activation in later stance was compensatory thus highlighting the fact that all crouch gait will not benefit from hamstring lengthening (45). The same group reported that crouch gait relied more on proximal muscles than unimpaired gait. This implies that this may be a feasible adaptation in the presence of neurological limitations rather than an abnormal pattern. A detailed comparison of plantarflexors revealed that the Gastrocnemius generated hip and knee flexion while the Soleus contributed to hip and knee extension in SLS. However, the role of the Gastrocnemius in plantar flexion is more significant than its action on the hip and knee. Thus lengthening Gastrocnemius in crouch gait can worsen crouch gait (42).

Thus modelling studies have shown that looking at specific times and functions of gait can yield clinically beneficial conclusions. However the effect of twinned phases and the contralateral muscles have not been described.

NEED FOR THIS STUDY

There is a need to describe the abnormalities in twinned phases of gait and identify corresponding primary and secondary/coping abnormalities in abnormal gait. This study attempts to take a first step to do so.

SUMMARY

Traditional gait analysis does not discriminate sufficiently between normal and pathological gait. However, specific phases like SLS and DLS and energy data have shown good discrimination in recent studies using mathematical modelling. Clinically beneficial outcomes have been described in literature with this approach including identifying key primary and secondary / coping responses which help to fine-tune soft tissues surgical interventions. However, twinned time phases like SLS-Swing and first and second DLS have not been described in these models even though these events happen at the same time on either limb. Hence this study attempts to address this need by studying abnormal gait in two twinned phases of SLS-Swing and first and second DLS.

CHAPTER THREE

AIMS AND OBJECTIVES

AIMS

1. To evaluate the feasibility of assessing gait abnormalities in two twinned phases of SLS-Swing and first and second DLS (SLS/DLS analysis)
2. To assess the feasibility of using SLS/DLS analysis to identify primary and secondary abnormalities in gait.

OBJECTIVES

1. To analyse SLS/DLS using the proposed protocol.
2. To describe the SLS/DLS abnormalities in gait collections.
3. To identify primary and secondary abnormalities using SLS/DLS analysis.

CHAPTER FOUR

METHODOLOGY

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SAMPLE

Sample size : Data from SLS-Swing (36 sets) and first and second double limb support (36 sets) phases from 18 abnormal gait records consecutively collected from 2009-2011 were analysed. Each gait record has the following sets: R SLS – L Sw, L SLS – R Sw, R DLS1 – L DLS2, R DLS2 – L DLS 1 where R = Right, L = Left, DLS 1 = first DLS, DLS 2 = second DLS.

Study design: Descriptive analytical (non-statistical) No randomisation or blinding was done for selection as this is a descriptive study. Anonymized data was used. Patient involvement was not required for this study.

Selection Criteria:

Inclusion Criteria

1. Each data set must be complete with kinematic, kinetic and electromyographic data
2. Each data set must have temporal data intact.

3. Both side collections and pure foot strike data

Exclusion Criteria:

1. Data collected prior to the SLS/DLS based software reports
2. Incomplete data within the set.
3. Noise or absent signal in data
4. Data collected from only one side

Dropped data:

Of the 22 gait analysis, there were 4 gait collections rejected due to incompleteness of gait recordings – one Gastrocnemius EMG was not collected, the force data from one collection had both feet striking the force plate, the ankle power data from one collection could not be processed and one gait collection was only done on one side.

INSTRUMENTATION

KINEMATIC DATA COLLECTION

The PhaseSpace kinematic system uses wired infrared light emitting diodes (LEDs) as markers. These are connected at the patient's side to a light control unit which in turn is connected by a long wire to the Administrating Unit at the computer area. This connects to the analogue digital card in the PC.

There are 14 LEDs which are taped on to standardised bony prominences in the lower limb as follows:

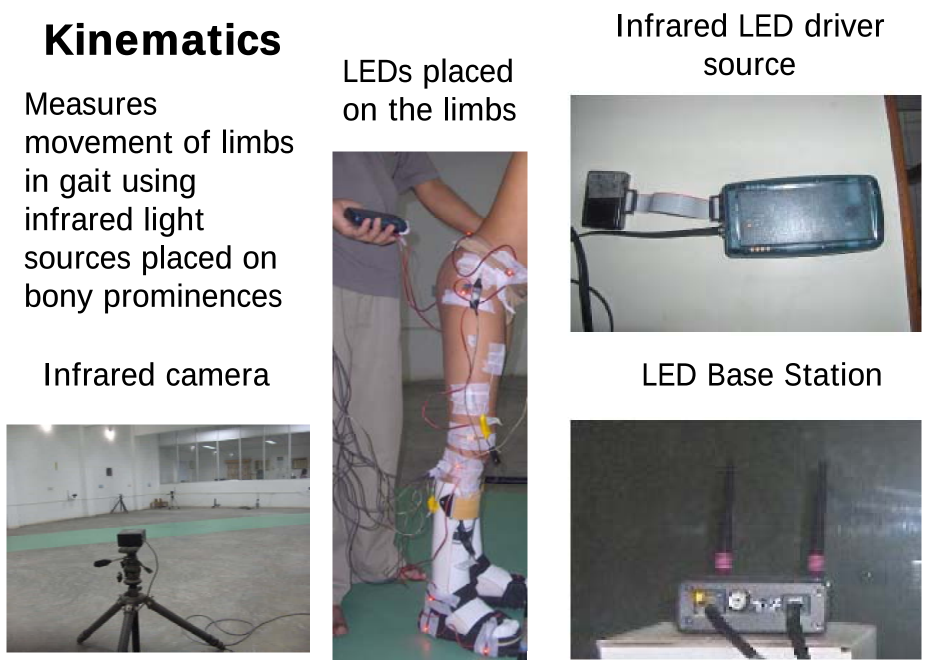
Ankle LEDs: 1 - head of 5th metatarsal 2 - lateral prominence of heel 3 - lateral malleolus.

Knee LEDs: 4 - fibular head.

Hip LEDs: 5 - lateral epicondyle of femur, 6 - anterior border of greater trochanter, 7 - Anterior superior iliac spine (ASIS).

One LED is attached to Sacrum making a total of 15 kinematic data points.

Fig 4.1: PhaseSpace kinematic 8 camera 3D infrared system



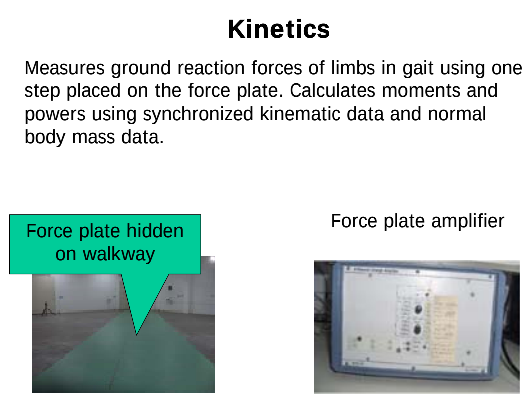
Before data collection the position of the cameras in the room are defined from a fixed point in the room with a set of 4 LEDs on a standardised frame called the Position Reference Structure (PRS). During data collection, the upper limb on the side facing the cameras must be placed on the opposite shoulder to prevent data loss at the hip. LED 2 is the main marker used by the software to delineate stance and swing. The angle made by the ASIS (LED 7) to the vertical is measured and manually entered to accurately measure hip flexion contracture.

Kinematic outputs were standardised: stick figure, angular velocity and angular displacements in the sagittal plane at the hip, knee and ankle against distance and against time. Software was developed to automate stance- swing marking based on the velocity of LED 2, calculations and measurements like stride length, stride time, percentage of stance, swing and single limb support time as a percentage of the gait cycle, walking speed and cadence. Stride length was normalised with effective leg length.

KINETIC DATA COLLECTION

Kinetic gait recording is made from a single KISTLER force plate camouflaged in the middle of the walkway. This is connected to a charge amplifier at the computer area. The patient should be able to have a single foot strike on the force plate without prior knowledge of this requirement to ensure optimal analysis.

Fig 4.2: Kistler single force plate kinetic system



DYNAMIC ELECTROMYOGRAPHIC DATA COLLECTION

Dynamic EMG recordings were obtained from 8 sets of surface electrodes with preamplifiers which are connected to the patient interface and transmitter unit on the patient's side. This, like the light control unit, is connected by a long wire to filter, control and display units at the computer area. This then connects to the analogue digital card in the PC.

Surface EMG positions were also standardised as follows:

Gluteus Maximus, Rectus Femoris, Tensor Fasciae Latae, Adductor Longus, Vastus Lateralis, Medial Hamstrings, Tibialis Anterior and Gastrocnemius.

These electrodes need to be strapped firmly over the muscles.

Software was devised to superimpose stance swing timing onto the dynamic EMG recordings.

Fig 4.3: Motion Labs dynamic EMG system

Dynamic Electromyography

Measures ground reaction forces of limbs in gait using one step placed on the force plate. Calculated moments and powers using synchronized kinematic data and normal body mass data.

EMG electrode

EMG Pre Amplifier

EMG Main Amplifier

The kinematic and EMG leads are connected to fairly heavy junction boxes which wire them to the computer. Though these are meant to be strapped onto the patient, their weight precluded this in the paediatric age group and hence they were carried separately by the parent or attendant.

ENERGY CONSUMPTION DATA COLLECTION

Heart rate recordings at rest and after walking for 20 meters were obtained by placing one of the surface EMG electrodes on the chest usually over the apex or sternum. Pectoralis major activity was rarely recorded on this electrode except when the patient used a walking aid.

DATA INTEGRATION

Hardware integration of these three systems were done by CMC's department of bioengineering. All data is therefore marked with temporal stance-swing times from the markers.

Fig 4.4: Integrated hardware in Gait lab

DOCUMENTATION

Gait analysis processing and output was done in the following aspects as mentioned before:

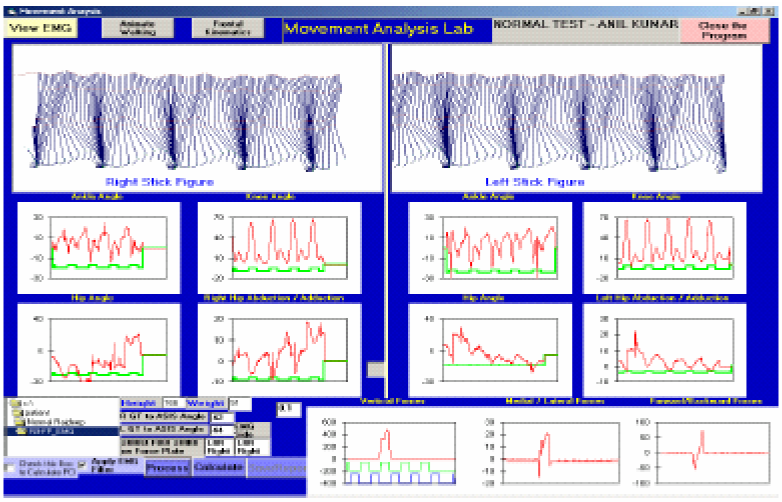
1. Kinematic analysis: Temporal related data - SLS as a percentage of swing, stride time, stance swing ratio, self selected walking speed (stride length / stride time) and cadence (2 / stride time) and Movement related data - stride length - actual and normalised (stride length / height)

Joint range of motion with SLS/DLS marking in addition to stance-swing.

2. Energy efficiency analysis: The resting and post exercise (after 20 m walk) heart rates were measured and PCI was calculated automatically.

3. Kinetic analysis: Moments and Powers at each joint with SLS/DLS marking in addition to stance-swing.

Fig 4.5 : CMC DAQ integrated Data processing and graph generation system



4. Dynamic EMG analysis:

The muscles recorded are chosen as representative of particular joint movements: Rectus Femoris for hip flexion, Gluteus Maximus for hip extension, Adductor Longus and Tensor fasciae latae for hip adduction and abduction respectively, Vastus Lateralis for knee extension, Medial hamstrings for knee flexion, Tibialis anterior and Gastrocnemius for ankle dorsiflexion and plantarflexion respectively.

ANALYSIS

Research design: Descriptive study

Statistical Analysis Plan: Descriptive statistics i.e. mean and standard deviation of all temporal /kinematic data for baseline

The data output from gait collections must be arranged in a standard format with ROM, Moments, Powers and EMG data identified on both right and left with DLS1, SLS, DLS2 and swing markings clearly identified. To make interpretation easy, these are all aligned and placed on a single page or screen.

Fig 4.6: SLS/DLS phase marking nomenclature

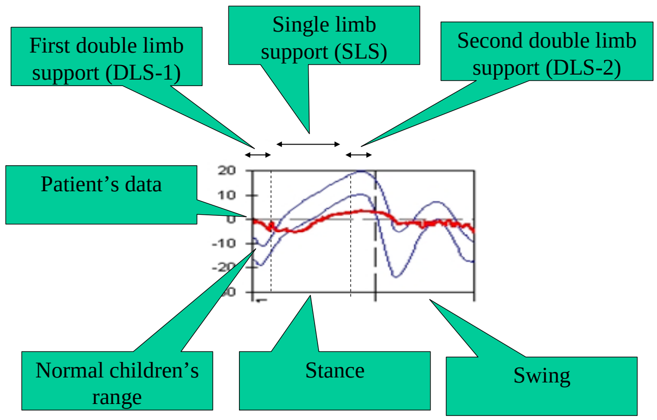
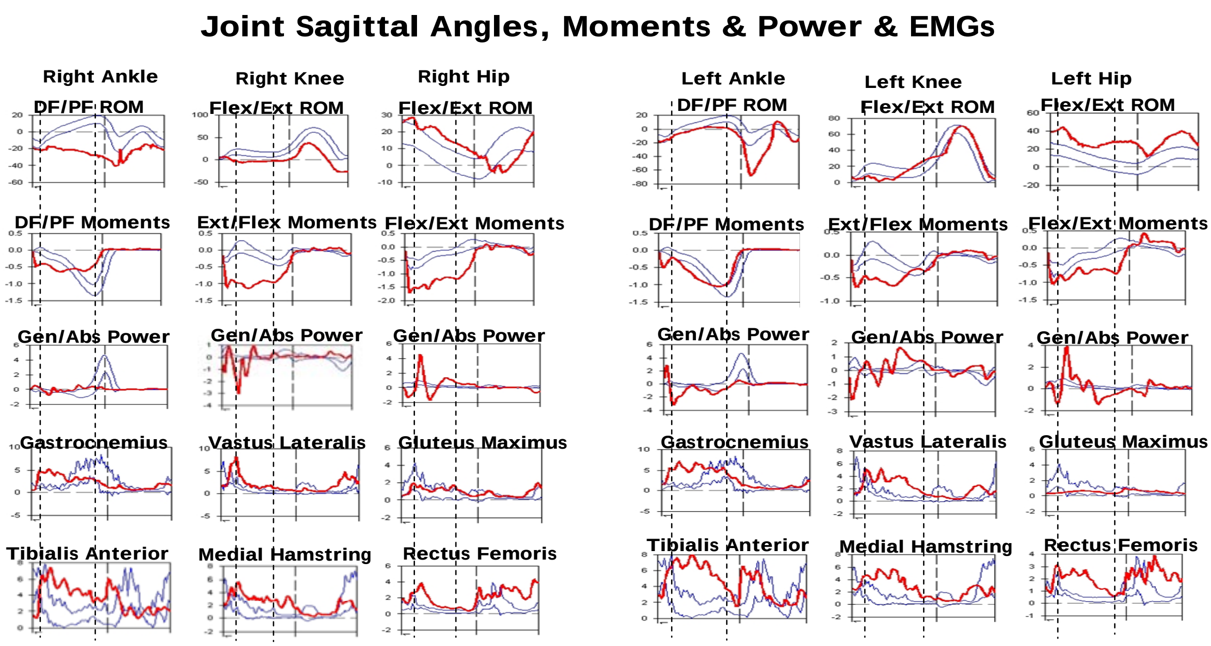


Fig 4.7: Full data output



The SLS/DLS analysis protocol was developed with the concepts outlined in the review of literature. As energy consumption is one of the more accepted and robust parameters and it measures one of the key gait functions of energy conservation by optimizing the pelvic movements, this was taken as the anchor to determine whether gait is abnormal in each phase or not.

First step: Power abnormalities were identified as either normal, excessive generation or excessive absorption in each of the 4 SLS/DLS constructs. Abnormality is defined as data outside the normative data identified by any area within the blue normative lines in each graph for the particular phase.

The reason for power abnormalities will necessarily have to be from abnormal lever arms in the biomechanical framework. The most prominent and commonly accepted lever arm which is modifiable and accounts for both neural and musculoskeletal control is muscle action. Therefore muscle abnormalities were identified in these phases.

Second step: For each power abnormality, corresponding muscle abnormalities in the same time frame were identified as described in Table 1.3 and Fig. 1.1:

e.g.

For right DLS1 ankle power abnormalities look for EMG abnormalities in the right ankle in DLS1, then right knee and hip in DLS1, then left ankle, knee and hip in DLS2.

For left SLS knee power abnormalities look for EMG abnormalities occurring in left knee SLS, then left ankle and hip in SLS, then right ankle, knee and hip in swing.

For right DLS2 hip power abnormalities, look for EMG abnormalities in right hip DLS2, then right ankle and knee and then left ankle, knee and hip abnormalities in DLS1.

Power generation occurs against gravity i.e. from concentric antigravity muscles or eccentric pro-gravity muscles. In our data, Gastrocnemius, Vastus Lateralis and Gluteus Maximus are taken as antigravity muscles and Tibialis Anterior, Medial Hamstrings and Rectus Femoris are taken as pro-gravity muscles.

Third step: Correlate the identified EMG abnormalities with the power generation abnormalities.

e.g.

if both right Vastus and Hamstrings are overacting in RSLS and the RSLS abnormality is excessive power generation, then the likely culprit is the right Vastus Lateralis.

Primary abnormalities in this study are identified as those abnormal muscle activities causing power abnormalities in the same side of the same joint. Secondary abnormalities are identified as abnormal muscle activity occurring at the same time as the power abnormality but from other joints on the same or opposite sides.

Fourth step: Identify the primary and secondary abnormalities in the phase under scrutiny.

e.g.

If a right knee SLS power generation abnormality is associated with a right SLS Vastus overactivity, this is a primary abnormality.

If a right knee DLS1 power generation abnormality is not associated with any right DLS1 EMG abnormality on knee, ankle or hip, but is associated with a left Vastus DLS2 abnormality, this is a secondary abnormality.

Eccentric and concentric muscle activity will affect clinical decision making and also potentially can change the direction of forces. Thus it is necessary to sub-classify primary and secondary muscle abnormalities into eccentric or concentric abnormalities. This is not possible from merely looking at the range of movement of the joint. This can be derived from the corresponding moment of the joint.

Fifth step: Determine whether the primary and secondary muscle abnormalities are a result of eccentric or concentric muscle contractions by deriving this information from the moment data.

e.g.

A restricted extension of knee may be due to an inadequate Vastus concentric contraction, excessive concentric hamstring contraction or an inappropriate eccentric hamstring contraction. At the point in time, if the Vastus Lateralis abnormality is associated with extensor moments, this is a concentric contraction. If the moments are flexor, the contraction is eccentric.

The data was finally collated into a cohesive explanation and justified.

SUMMARY

This descriptive study SLS/DLS analysis was based on abnormal gait data.

Kinematic, Kinetic and energy data from 36 complete bilateral instrumented gait collections were analysed using an SLS/DLS protocol which is based on the primacy of energy efficiency and muscle contraction with regards to specific times and functions on both sides at the same time.

The steps undertaken for this SLS/DLS gait analysis were:

1. Generate SLS/DLS output
2. Identify abnormalities in power in SLS and DLS

3. Identify corresponding muscles which are abnormal in time
4. Match the power and EMG abnormalities to differentiate primary and secondary abnormalities - Correlation of timing of power abnormalities with kinetic, kinematic and EMG data at the same time and in the same joint were identified as primary abnormalities. Data from other joints on either side were identified as secondary abnormalities
5. Identify concentric / eccentric EMG abnormalities among these based on corresponding moment direction
6. Interpret the data clinically.

CHAPTER FIVE

RESULTS

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BASELINE DATA AND SAMPLE

The study included 36 gait collections (18 pairs) taken from abnormal gait data collected in the Movement Analysis Laboratory, Rehabilitation Institute, Christian Medical College, Vellore from 2009-2011.

The baseline information shows that the gait collections come from mostly children and young adult patients with a mean age of 10.8 ± 5.6 and a range of 3-25. All such values are presented in the format of Mean ± standard deviation. Thirteen pairs of gait collections belonged to males, six gait collections belong to females. All were referred for specific spastic gait questions relating to planning of surgical or orthotic interventions from the departments of Physical Medicine & Rehabilitation or Paediatric Orthopaedics. As with other bioengineering gait studies (37), no further clinical data was taken for the study as the study is purely based on the biomechanical data harvested from the gait collections, rather than the clinical data of human subjects.

BIOMECHANICAL DATA OF SAMPLE

Two sets of data were collected only once i.e. 18 times – walking speed and Physiological Cost Index. All other data was collected from all 36 collections.

Walking speed of the 36 collections averaged at 39 ± 10.4 metres/min. Normalized data from our lab is 47 ± 15 metres / min.

The Physiological Cost index averaged at 1.8 ± 1.9 with a range of 0.29 – 8.7. The normalized value of this lab is 0.29 ± 0.17. One value of 8.7 was noted to be an outlier and if not for this value, the mean PCI would have been more reasonable at 1.4 ± 0.8.

As there is a wide variation of height, the stride length is normalized to height (stride length / height) as mentioned before. The average normalized stride length of the 36 collections was 0.5 ± 0.1 with a range of 0.2 - 0.8. The normalized data of this lab is 0.78 ± 0.06.

The percentage of time in the 36 gait cycles spent in stance averaged 61.4 ± 5.7 (range from 46 – 76) % - the normal being 60%. Single limb support time from the 36 collections expressed as a percentage of the gait cycle was 38.2 ± 5.4 (range 24 – 50) %. Our lab normative data is 40 ± 5 %.

SLS/DLS ANALYSIS

The protocol outlined in the methodology section was carried out for 36 collections to identify the biomechanical abnormalities in the 4 phases. These are presented separately in Power, EMG and range of movement sections. The moments are presented but not emphasized in an individual format because they vary with each individual and analysing individual data may not yield clinically relevant information by themselves. However, they are used in the collated data analysis to identify concentric or eccentric abnormalities of muscle function.

POWER DATA IN SLS/DLS ANALYSIS

Data from 36 gait collections are presented according to the phase in time for each subset of data at ankle, hip and knee. As the power data forms the foundation of SLS/DLS analysis, this is presented first.

The symmetricity of the data was partial as shown in Table 5.1:

Table 5.1: Symmetrical power data

No. of symmetrical collections (n = 18 pairs)	DLS1	DLS2	SLS	Swing
Ankle	8 (40%)	16 (89%)	13 (72%)	16 (89%)
Knee	8 (40%)	10 (55%)	8 (40%)	13 (72%)
Hip	9 (50%)	9 (50%)	10 (55%)	8 (40%)

POWER DATA DURING FIRST DOUBLE LIMB SUPPORT (DLS1)

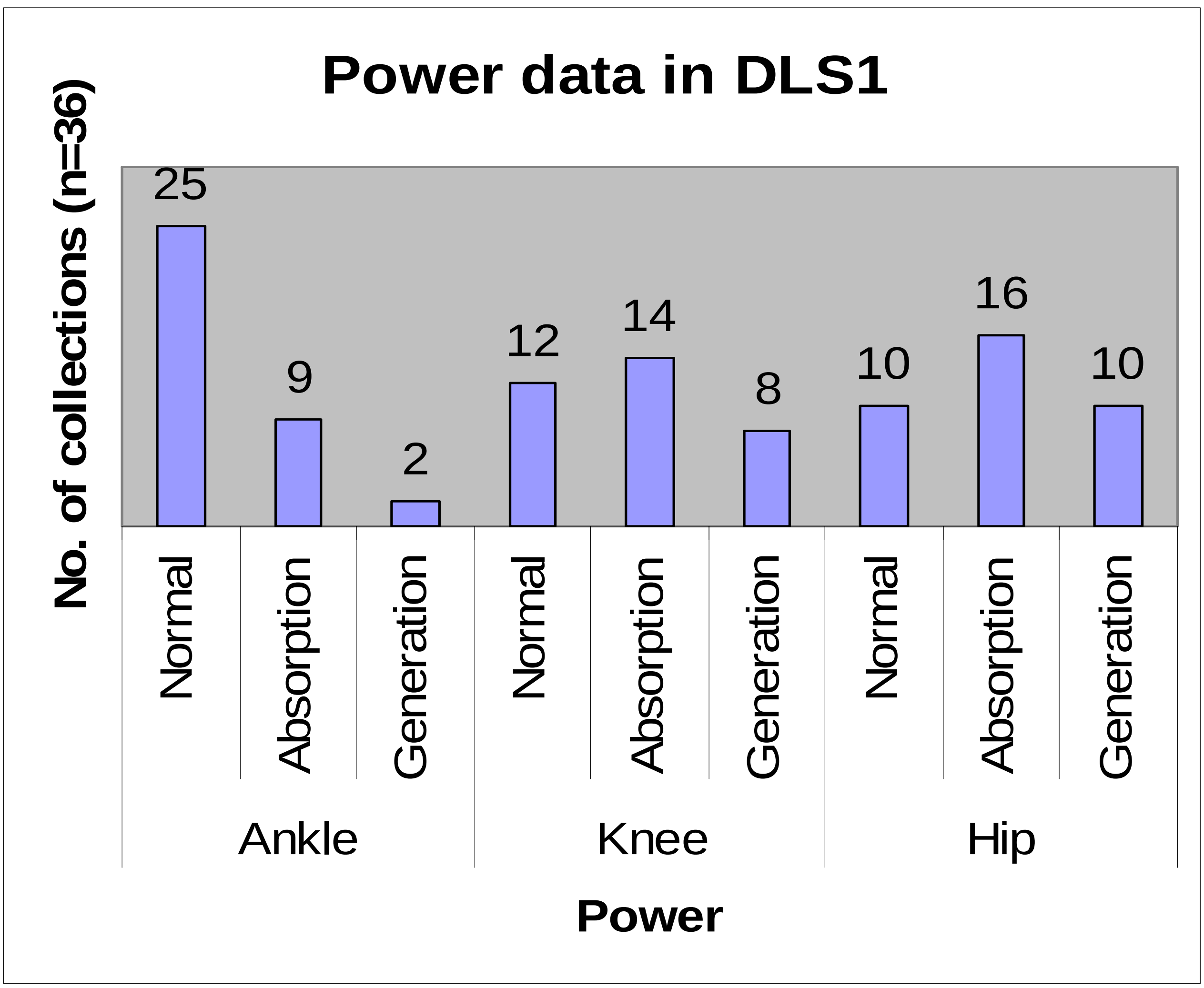
Ankle: 25 (70%) of the 36 collections were normal. The next common occurrence was abnormal absorption of energy occurring in 9 (25%) of the collections.

Knee: In the knee, the abnormalities were equally distributed with 12 (33%) normal, 14 (39%) showing abnormal absorption pattern and 8 (22%) showing abnormal generation patterns. Potentially the 39% showing abnormal absorption patterns would experience worse energy efficiency rather than those with normal or generation patterns.

Hip: 10 (28%) showed normal power characteristics, whereas 16 (44%) showed abnormal absorption and 10 (28%) showed abnormal generation.

In all these data, there were some abnormal biphasic patterns i.e. absorption followed by generation and vice versa. Since their frequency of occurrence was only 1-5, they were classified along with their first abnormality i.e. absorption-generation pattern was classified along with absorption and generation-absorption patterns along with generation patterns.

Fig 5.1: Power data in DLS1



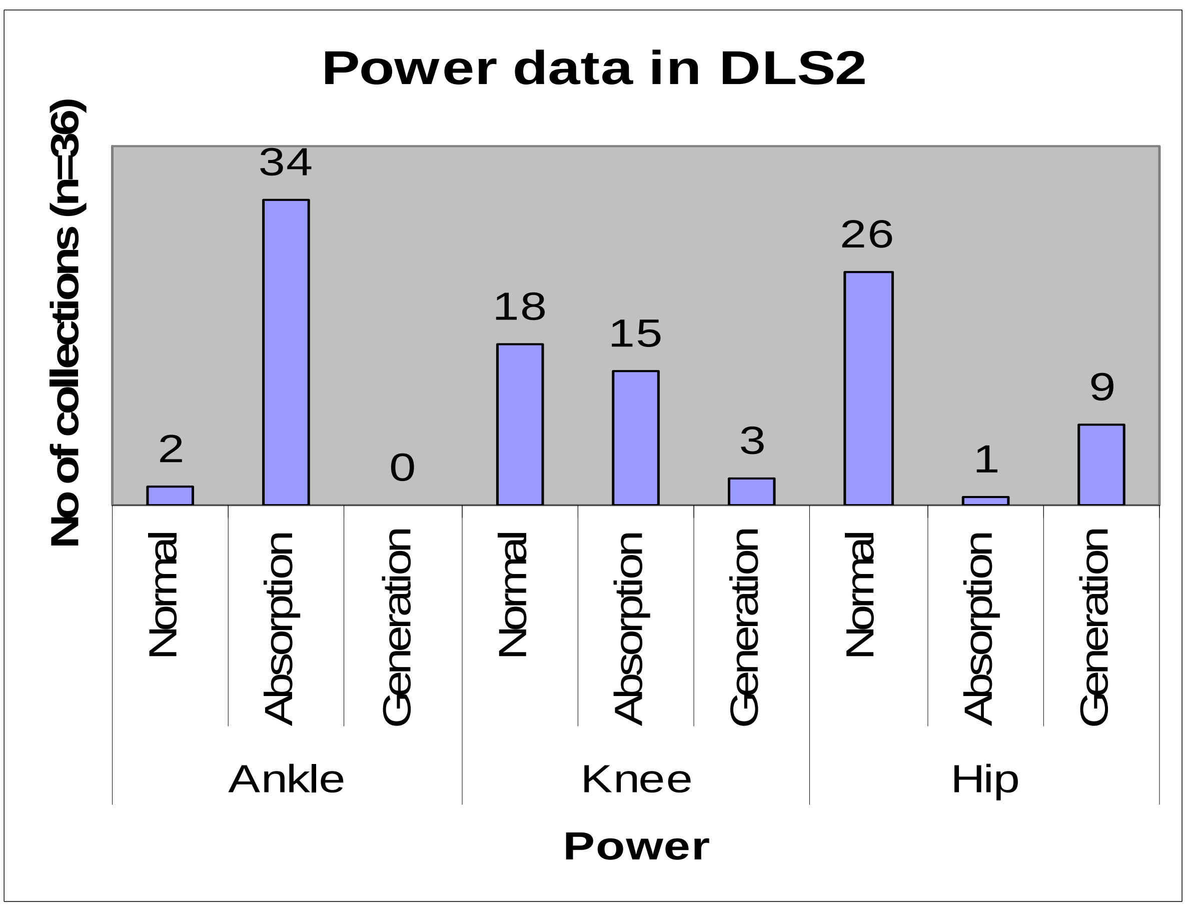
POWER DATA IN SECOND DOUBLE LIMB SUPPORT (DLS2):

Ankle: A very significant almost global abnormality was noted in all the graphs. Normally, in DLS2, the ankle produces a very strong push off force called *A2 power generation*. In all graphs these were either missing and even in the 2 labelled as normal because A2 was seen, they were very tiny (but within normal limits of our normative data and therefore technically normal).

Knee: The prominent abnormalities – 15 (41%) noted were absorption, but a reasonable number 18 (50%) showed normal pattern.

Hip: Most of the collections – 26 (72%) showed normal patterns.

Fig 5.2: Power data in DLS2



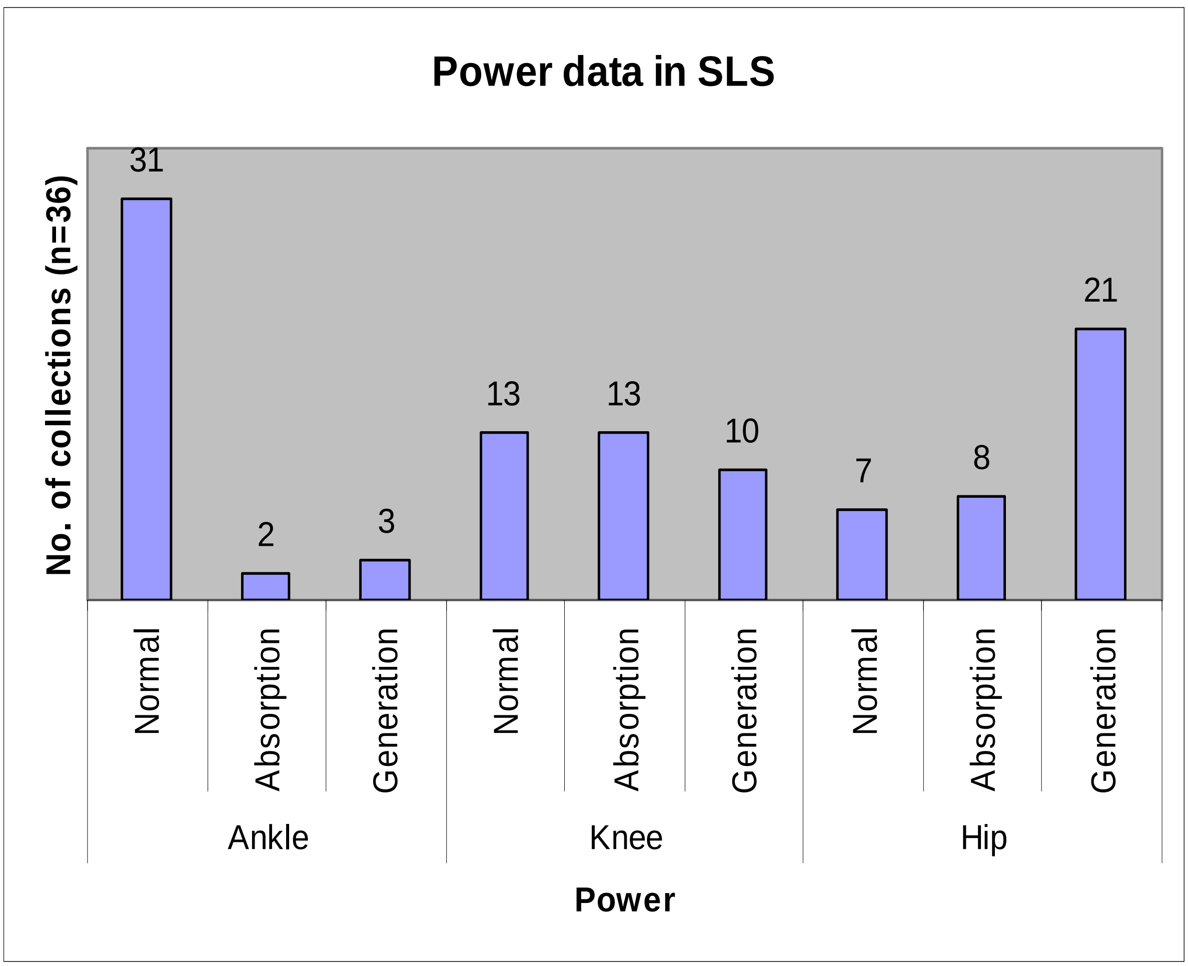
POWER DATA IN SINGLE LIMB SUPPORT (SLS)

Ankle: A very strong predilection is noted for normal patterns in SLS – 31 (86%).

Knee: As with other knee data, here the patterns are almost equally distributed between normal, abnormal absorption and generation (see Fig 5.3).

Hip: The prominent pattern in SLS is hip generation in 21 (58%) of the collections.

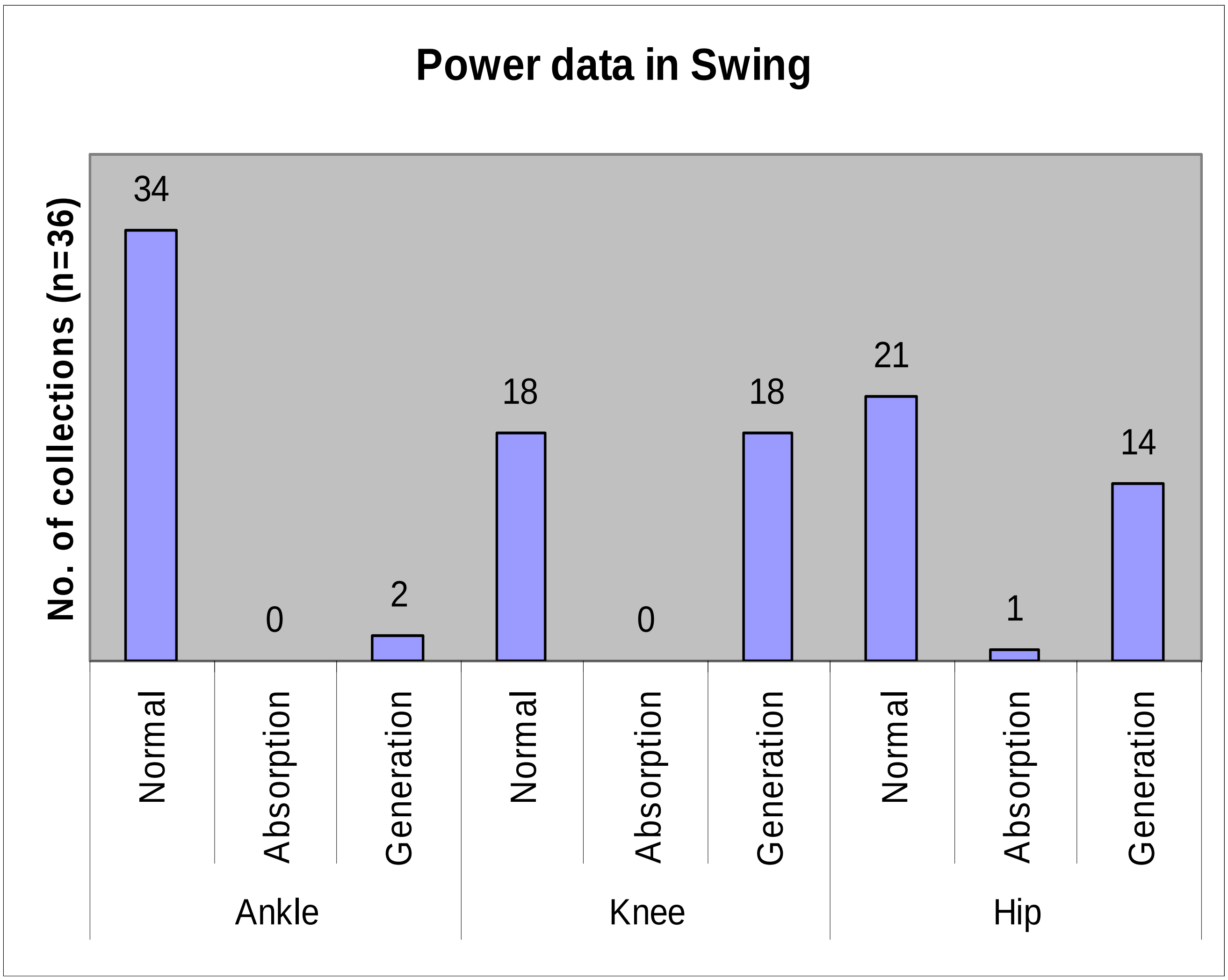
Fig 5.3: Power data in SLS



POWER DATA IN SWING (Sw)

As shown in Fig 5.4, most of the patterns noted are not worrying in that they are either normal (especially at the ankle – 31 (94%)) or power generating patterns.

Fig 5.4: Power data in Swing



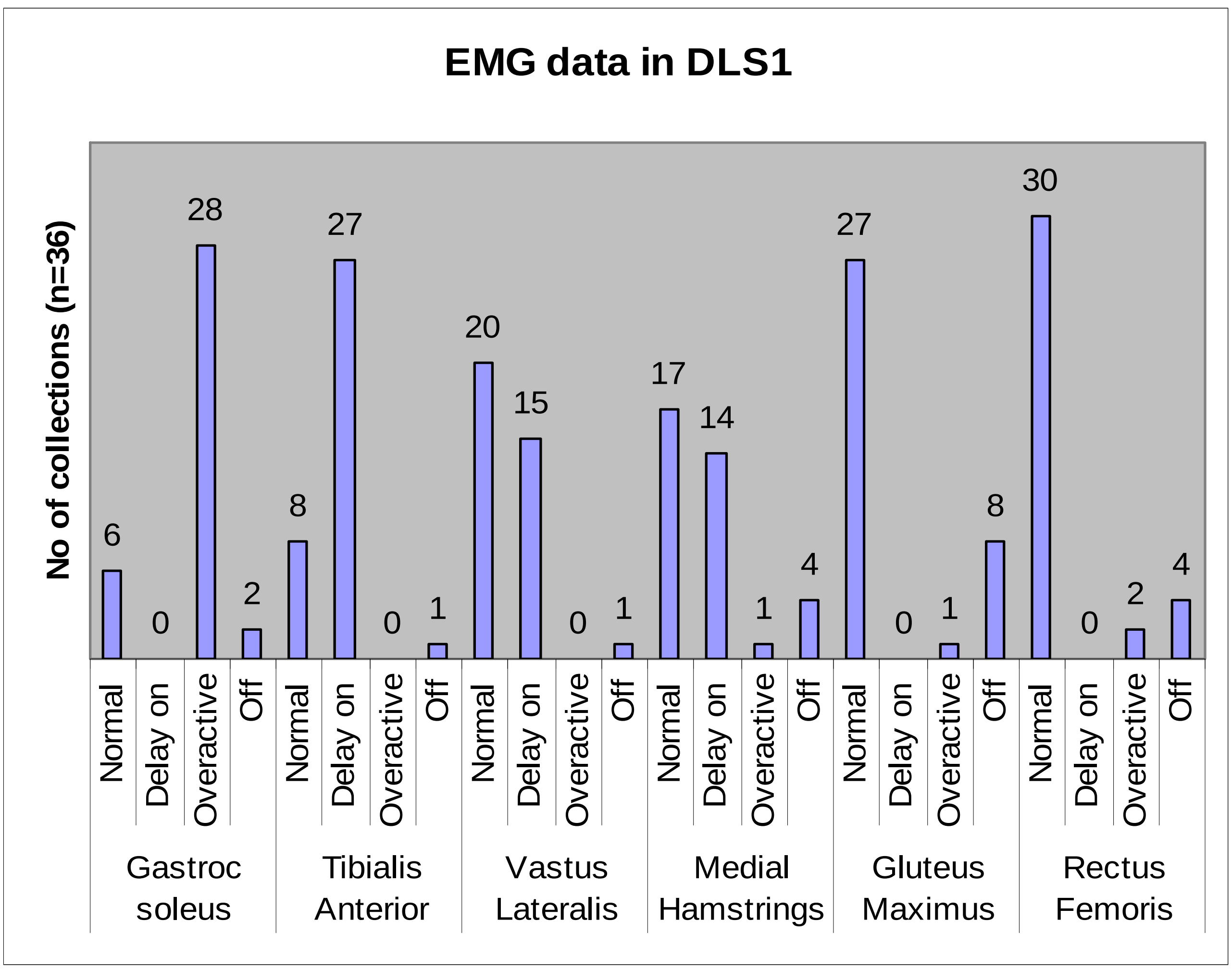
EMG DATA IN DLS1

In DLS1, the early onset of abnormal Gastrocnemius activity was a prominent finding in 28 (78%) of the collections. Similarly, delayed onset of initiation of Tibialis Anterior was commonly seen in 27 (75%) of the collections.

In the knee, Vastus and Hamstrings commonly acted together in around 40% of the collections with a delayed onset of initiation at the transition from DLS1 to SLS.

The hip was characterized by mostly normal EMG patterns in 75-83% of the collections.

Fig 5.5: EMG data in DLS1



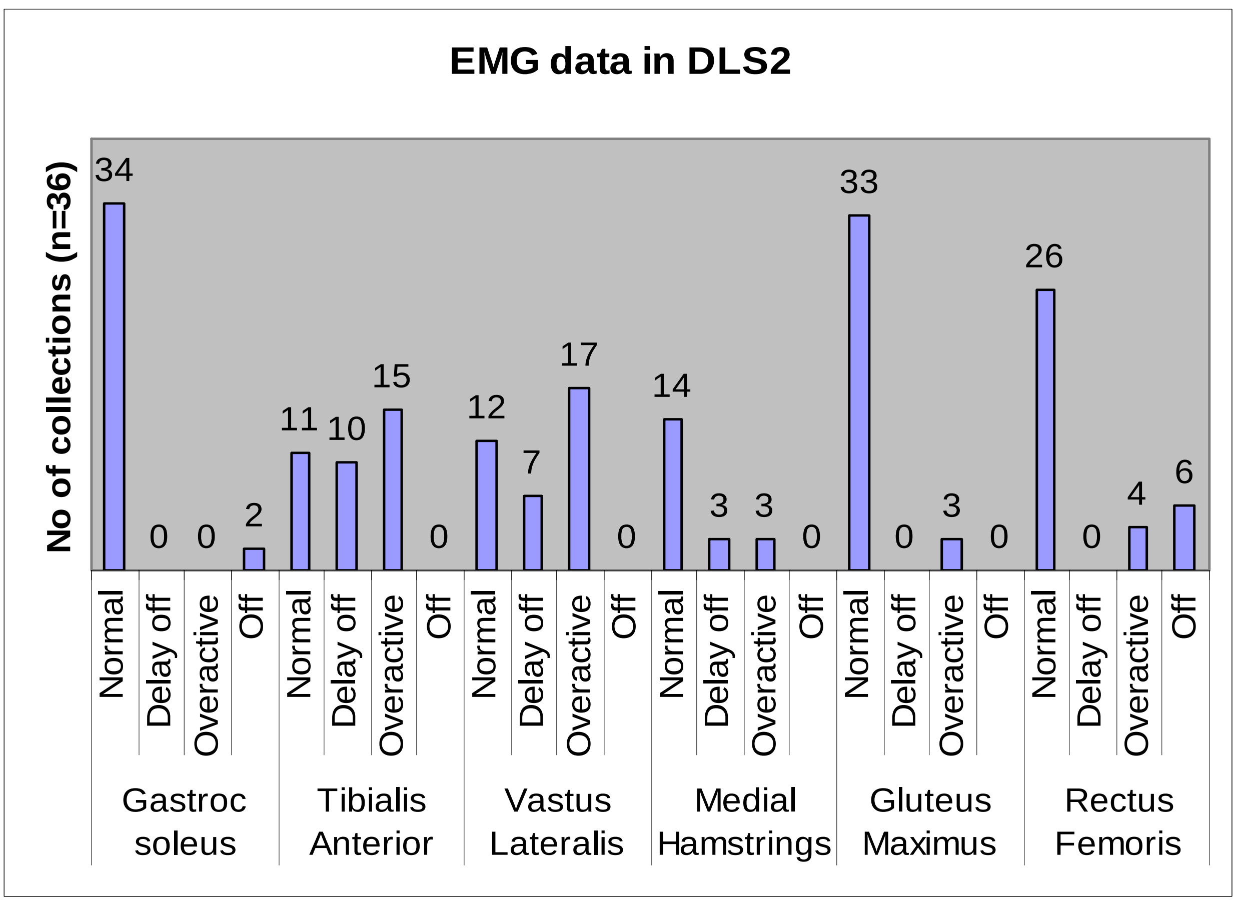
EMG DATA IN DLS2

The most common finding in this study was the absence of A2 power generation in the ankle in DLS2. This, strangely, was associated with a normal pattern of Gastrocnemius EMG in the same phase in 34 (94%) of the collections and this interesting paradox will be discussed later on. No similar consistency was seen in the Tibialis Anterior which had equal proportions of normal, delayed or over-activity in DLS2 – around a third of each type.

In the knee too, Vastus and hamstrings showed similar distributions of activity.

As in DLS1, the hip EMGs were mostly normal (72 - 91% of the collections).

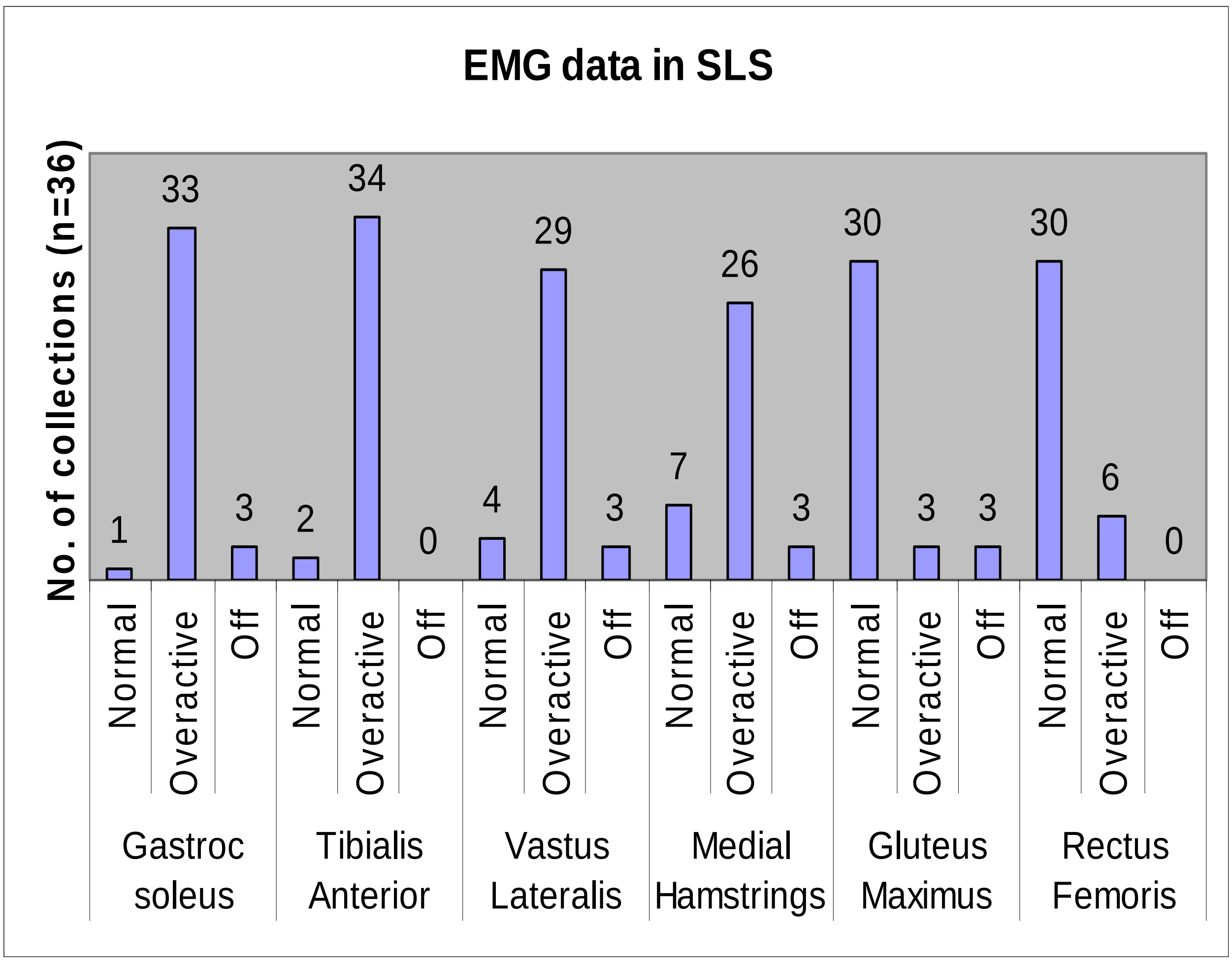
Fig 5.6: EMG data in DLS2



EMG DATA IN SLS

In SLS, co-activation (or co-contraction) was a prominent finding in the ankle and the knee. Tibialis Anterior and Gastrocnemius were overactive together in above 90% of the collections. Similarly, Vastus and hamstrings were co-contracting in more than three-quarters of the collections. As in the other phases, normal hip EMGs tend to dominate the collections in more than 80% of the collections.

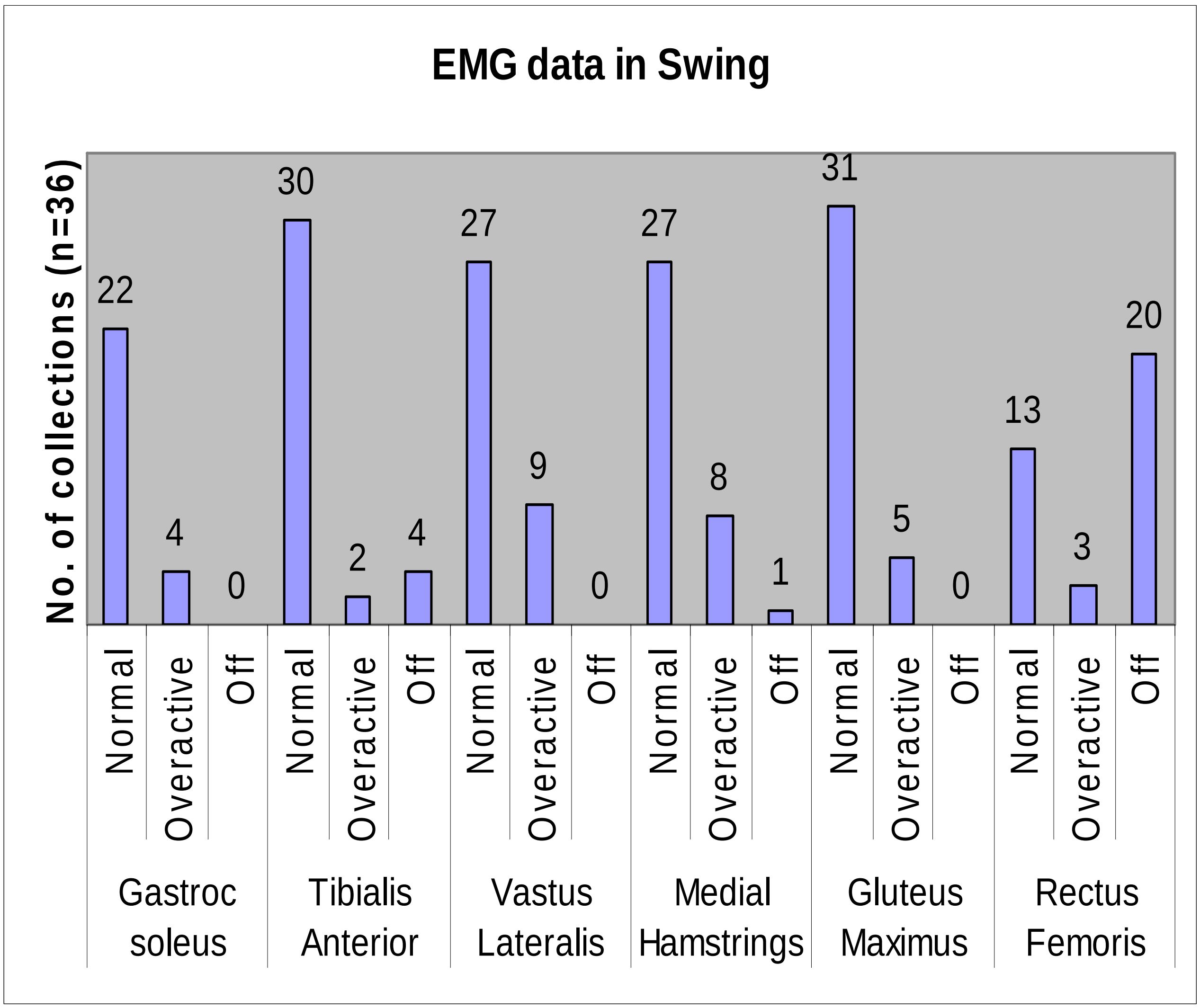
Fig 5.7: EMG data in SLS



EMG DATA IN SWING

Except for the absence of a mid-swing peak of Rectus Femoris in more than half of the collections, the EMG patterns seen in swing were mostly normal.

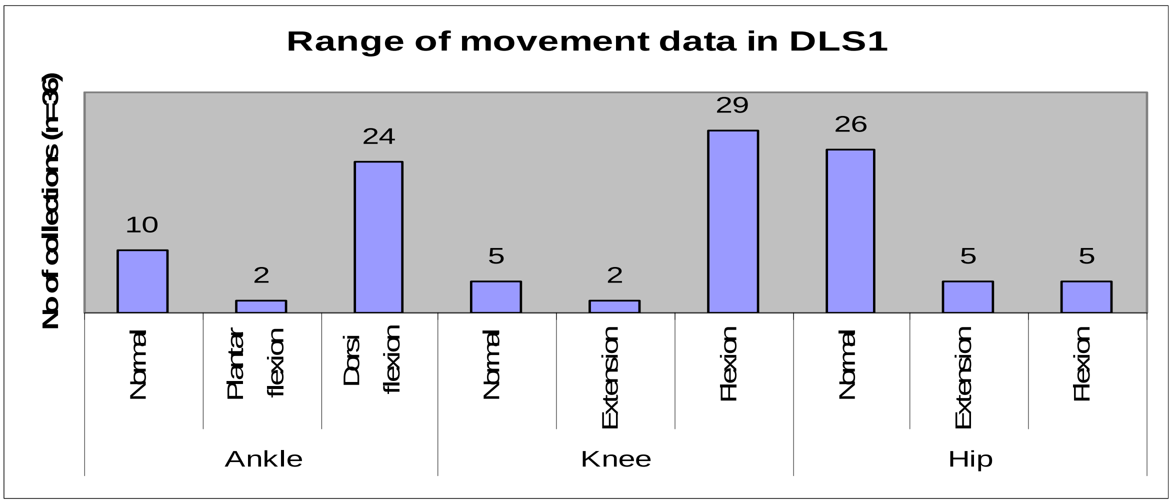
Fig 5.8: EMG data in swing



ROM DATA IN DLS1

The range of movement in gait is the result of abnormalities and coping mechanisms interacting to form a visible pattern of gait. DLS 1 is a very short period to make out with the eye, but data shows that the common pattern is excessive ankle dorsiflexion and knee flexion with a normal hip pattern.

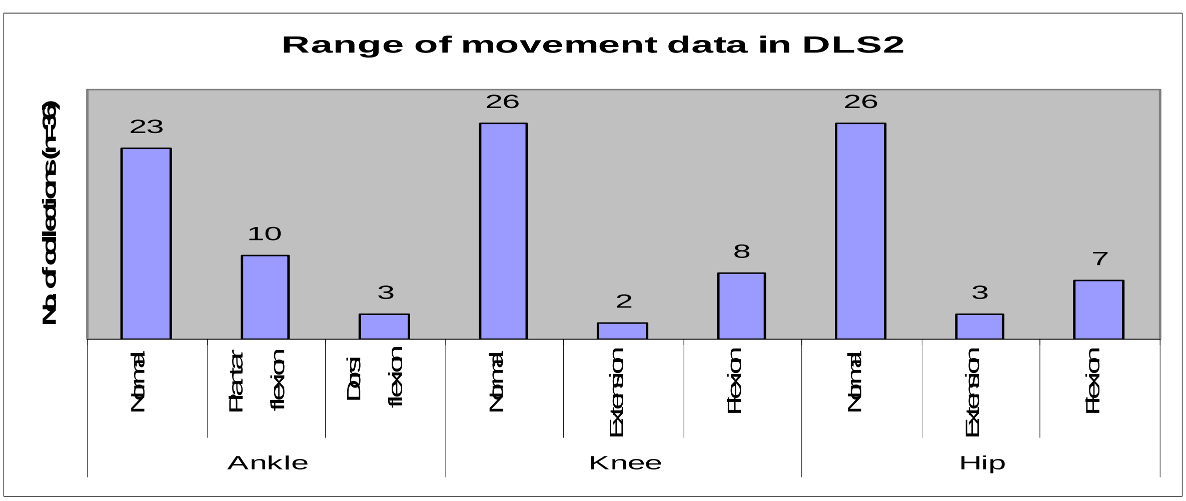
Fig 5.9: ROM data in DLS1



ROM DATA IN DLS2

The gait pattern in DLS2 is mostly normal in more than 60% of the collections of the ankle, knee and hip.

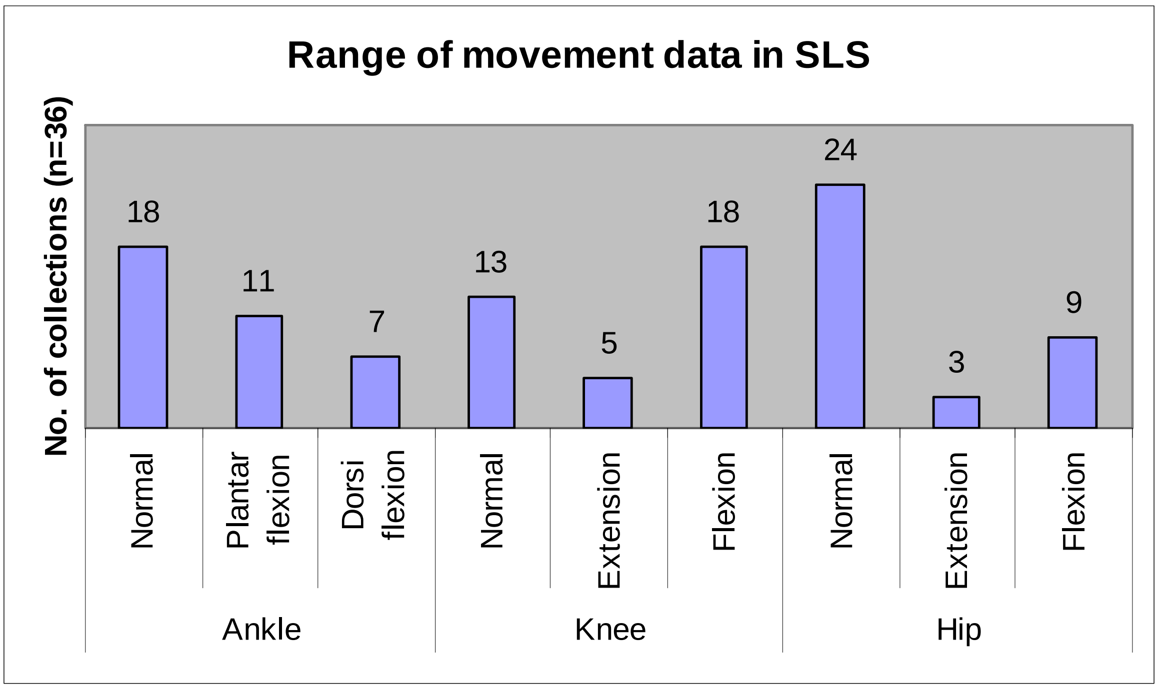
Fig 5.10: ROM data in DLS2



ROM DATA IN SLS

This is the most visible part of stance and the common pattern of movement is a normal ankle rocker and hip movement in more than half the collections though the knee was flexed in half the collections.

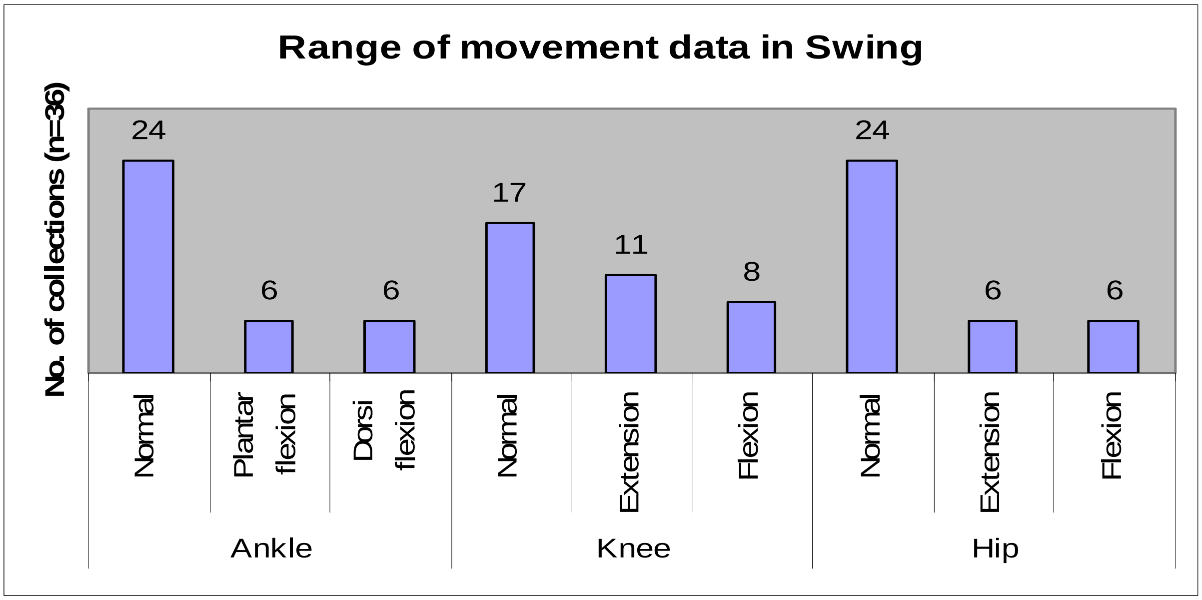
Fig 5.11: ROM data in SLS



ROM DATA IN SWING

This is also an easily visible part of gait. As with EMG data, the swing phase range of movement in ankle, knee and hip were mostly normal, though some variability was noted at the knee (inadequate flexion in 11 (30%) of the collections.

Fig 5.12: ROM data in swing



MOMENTS DATA

This data, as expected, varies widely with muscle activity and indicates whether the activity was concentric or eccentric. Classification into patterns is not possible with this analytical technique with the exception of swing moments which are almost universally normal in more than 80% of the collections.

DLS1:

Ankle: Normal 12 (33%), Plantar flexor moments 17 (44%), Dorsiflexor moments 7 (19%).

Knee: Normal 8 (22%), Extension 11 (30.5%), Flexor moments 17 (47%).

Hip: Normal 6 (16.7%), Extension 15 (42%), Flexion 15 (42%).

DLS2:

Ankle: Normal 18 (50%), Plantar flexor moments 2 (5%), Dorsiflexor moments 16 (45%).

Knee: Normal 14 (39%), Extension 13 (58%), Flexor moments 9 (25%).

Hip: Normal 15 (42%), Extension 16 (45%), Flexion 5 (14%).

SLS:

Ankle: Normal 11 (31%), Plantar flexor moments 3 (8%), Dorsiflexor moments 22 (61%).

Knee: Normal 12 (33%), Extension 15 (42%), Flexor moments 9 (25%).

Hip: Normal 7 (19%), Extension 21 (36%), Flexion 8 (22%).

Swing:

Ankle: Normal 34 (94%), Plantar flexor moments 1 (3%), Dorsiflexor moments 1 (3%).

Knee: Normal 31 (86%), Extension 3 (8%), Flexor moments 2 (5%).

Hip: Normal 29 (80%), Extension 1 (3%), Flexion 6 (17%).

COLLATING AND INTERPRETING SLS/DLS DATA

The above data is summarised below to begin an interpretation which is based on the commonest abnormalities noted in each twinned phase.

DLS1-DLS2 ANALYSIS

The results show that the primary power abnormalities in DLS1-DLS2 are:

1. DLS1 knee power absorption.

   DLS1 knee power absorption with a flexor moment cannot be explained by DLS1 ipsilateral EMG abnormalities (they are largely normal in DLS1 and an overactive Gastrocnemius should have produced a power generation). However, the opposite limb in DLS2 at the same time shows concentric Tibialis Anterior, eccentric Vastus and concentric Hamstring over-activity all of which can explain the DLS1 abnormality.

2. DLS1 hip power absorption.

DLS1 hip power absorption with either flexor or extensor moments again cannot be explained by DLS1 ipsilateral EMG abnormalities as they are largely normal.

However a flexor moment can be explained by a concentric DLS2 contralateral hamstring acting at the same time and an extensor moment can be explained by an eccentric Vastus.

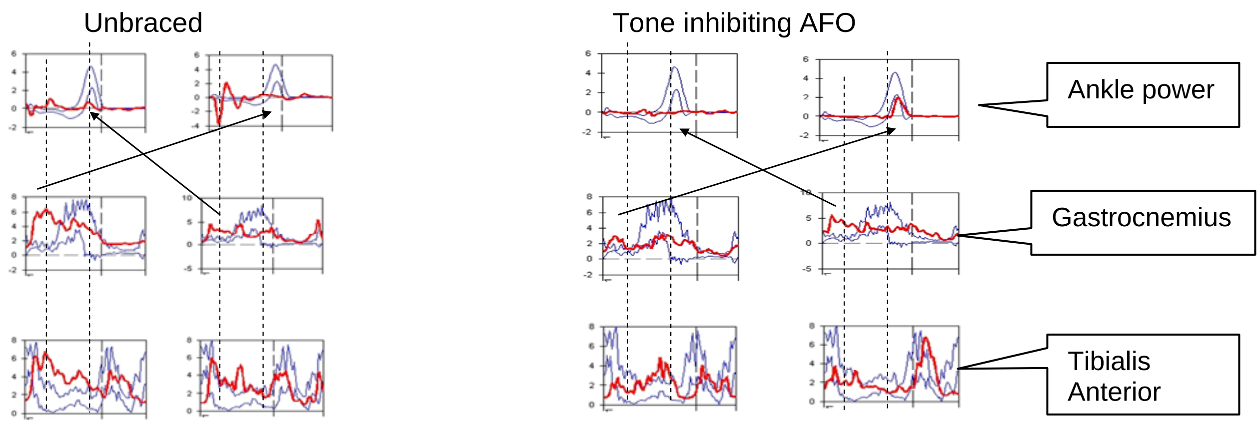
3. DLS2 absent A2 power generation at ankle.

   This abnormality is present in almost all collections. There are several EMG abnormalities in DLS2 – co-activating (co-contracting) Vastus and Hamstrings and overactive Tibialis Anterior ipsilaterally. Contralaterally too, in DLS1, there are delayed onset Tibialis Anterior and early over-activity of Gastrocnemius and on occasion, delayed Vastus and Hamstring activity. Notably, no hip EMGs are abnormal. However, to explain the lack of power generation, the most elegant explanation would be concentric ipsilateral DLS2 Tibialis Anterior over-activity and concentric contralateral DLS1 Gastrocnemius over-activity. When the Tibialis Anterior is normal (around 30% of the collections), then the contralateral Gastrocnemius may be the only muscle to blame for a lack of A2 generation. Though this may appear to be counter-intuitive, a case study showing this to be the case is presented below wherein shutting off the DLS1 Gastrocnemius with a tone inhibiting AFO on one side, restored the contralateral A2 and vice versa.

The ankle gait analysis of a subject with mild spasticity is shown below. The question was which spastic muscle was the primary cause of the gait abnormality.

Fig 5.13 clearly shows the usual absent A2 power generation curve in both ankles in DLS2. However, no abnormality is noted in the ipsilateral EMGs of the ankle shown below – and indeed in all the other ipsilateral muscles. This dilemma is resolved with DLS1-DLS2 analysis. The early onset of the contralateral spastic Gastrocnemius in DLS1 is shown up as the cause for an absent A2 as is seen in the un-braced graphs of power and Gastrocnemius activity in Fig 5.13.

Fig 5.13: Example of A2 absence affected by opposite Gastrocnemius



This hypothesis is confirmed when a gait collection is taken with a tone inhibiting ankle foot orthosis (AFO) as seen on the right side graphs in Fig 5.13. The tone inhibition worked only on one side – the longer left arrow shows the successful tone inhibition of Gastrocnemius resulting in the emergence of contralateral A2 and the unsuccessful early onset Gastrocnemius spasticity persisting resulting in continued A2 absence on the opposite side.

Thus, on analysing collated DLS data, there is evidence to show that abnormal muscles on both sides would explain some of the common abnormalities seen in abnormal gait.

SLS ANALYSIS

The results show that the primary abnormality in the power data in SLS is a hip power generation. There are sufficient EMG abnormalities on the same side, though not at the hip, to explain this: co-contracting Vastus and Hamstrings and co-contacting Gastrocnemius and Tibialis Anterior are common abnormalities. The contralateral swing phase Rectus abnormality is not evoked as it does not produce a power abnormality. Indeed, for all practical purposes, swing phase abnormalities do not seem to affect the analysis. Also, since the abnormality is a power generation, this will probably help to improve energy efficiency of gait and thus may be a compensatory mechanism.

Thus the collated data analysis shows that SLS/DLS analysis in a useful method of analysing primary and secondary abnormalities and it especially highlights the effect of muscles from both limbs on gait abnormalities.

CASE STUDY: DIAGNOSING USEFUL SPASTICITY USING SLS/DLS ANALYSIS

A case study is described to highlight the use of SLS/DLS in clinical decision making. The question posed is whether the subject will benefit from a tone inhibiting device, in this case a medial arch support with toes in dorsiflexion.

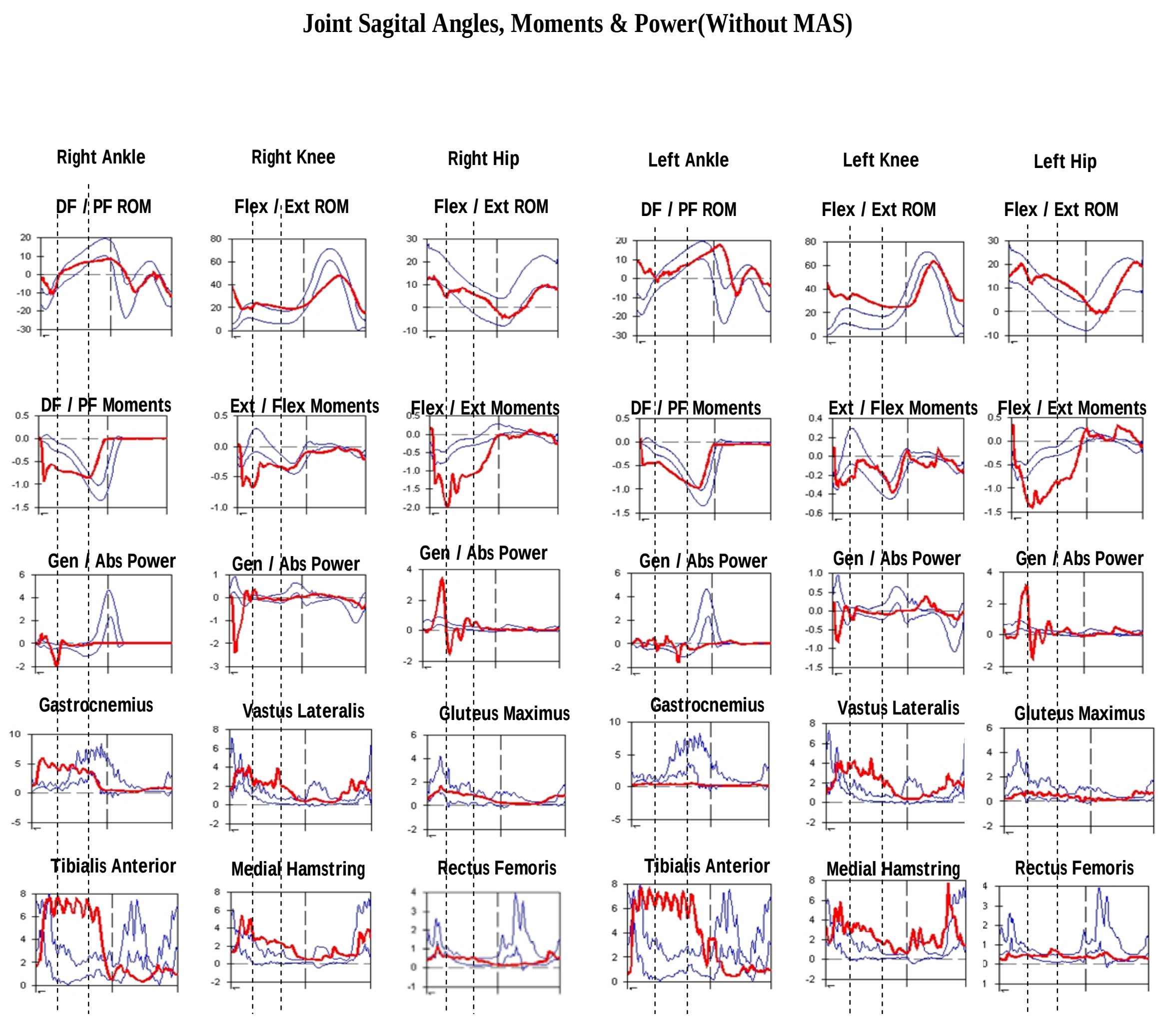
The gait collection without the tone inhibition shows the following power abnormalities (Fig 5.14):

1. Bilateral absent A2 power generation in both DLS2
2. Power absorption surge in bilateral knee in DLS1
3. Power generation followed by a little absorption in hip in SLS

The EMG analysis looking for the cause for the above shows that:

1. Right A2 absence is caused by an absent ipsilateral Gastrocnemius with an overactive eccentric Tibialis anterior in DLS2 (primary abnormality). The inadequate contralateral Rectus Femoris in DLS1 allowing excessive hip extension whip may also contribute. Left A2 is the same with the additional problem of an early onset of right DLS1 gastrocnemius (secondary abnormality).

Fig 5.14: SLS/DLS output without tone inhibiting medial arch support

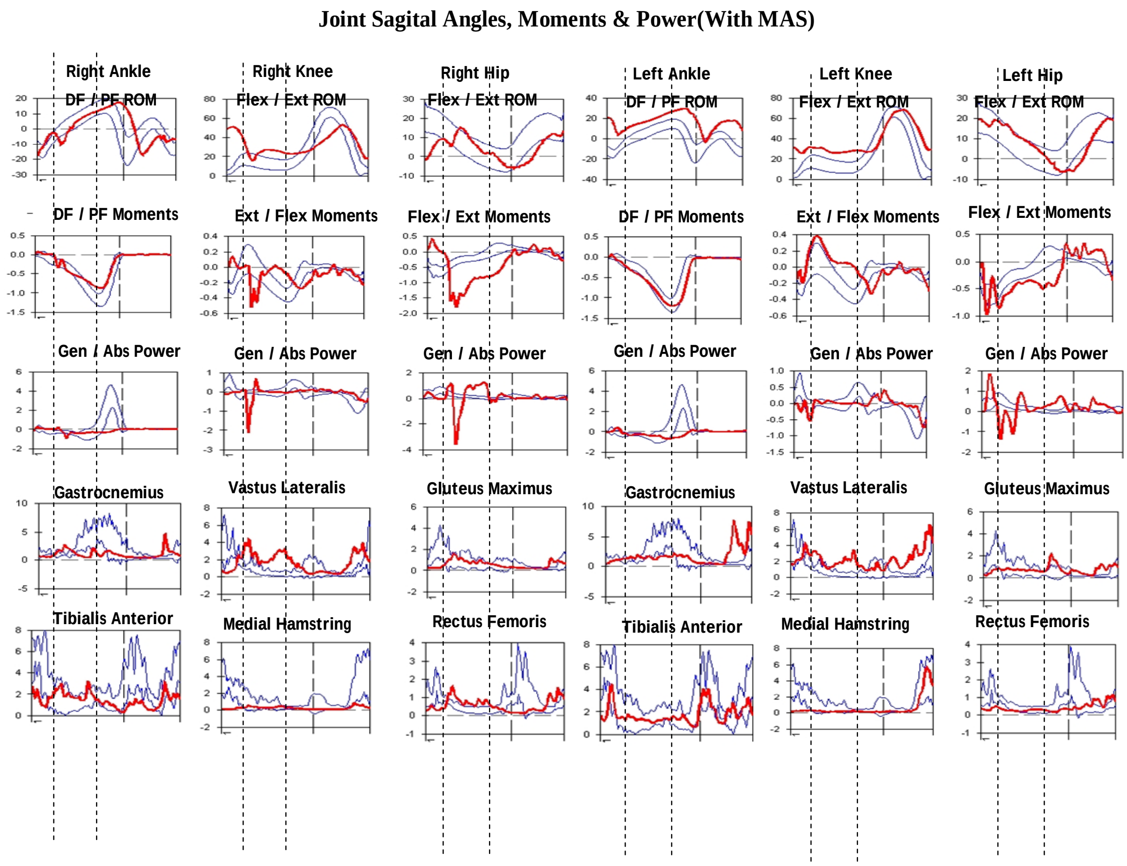


2. Power absorption surge in bilateral knee is caused by delayed onset of ipsilateral Vastus and Hamstring at the same time in DLS1 (primary), contralateral Gastrocnemius is off and Tibialis Anterior is eccentrically overacting in DLS2 (secondary).

3. There are no corresponding hip muscle abnormalities to explain the transitional DLS1-SLS power surge. However, delayed onset eccentric Tibialis Anterior, eccentric Vastus and concentric Hamstring and right absent and left overactive concentric Gastrocnemii will cause this secondary abnormality.

Thus with SLS/DLS analysis, the primary abnormalities are right Gastrocnemius off in DLS2, left Gastrocnemius off in DLS1 and DLS2, delayed onset of Vastus and Hamstring in DLS1-SLS transition. Spasticity does not seem to be the main reason for the abnormality. Rather the main reason seems to be poor ankle and knee voluntary control. Therefore tone inhibition is unlikely to help.

Fig 5.15: SLS/DLS output with tone inhibiting medial arch support



This may be confirmed with the gait record of the same person wearing the tone inhibiting device. The physiological cost index (PCI) increased from 1 to 1.1 after wearing the device which in itself is an indicator that the device increases energy cost of walking.

The power abnormalities after wearing the tone inhibiting device are seen in Fig 5.15 and are just the same as before with one exception – the secondary power generation abnormality at the hip (which might have been compensating to provide some energy efficiency) has now become a power absorbing abnormality. This would also explain the increase in PCI. The evidence that the medial arch and toe dorsiflexion did inhibit tone is seen in the correction of Tibialis Anterior and right Gastrocnemius EMG abnormalities.

Thus the SLS/DLS analysis indicated that improving voluntary control is the primary treatment for this subject rather than tone inhibition. The gait collection with the tone inhibiting device has shown that this is indeed true.

SUMMARY

SLS/DLS analysis revealed interesting and hitherto undescribed gait patterns involving interactions between both the limbs which may have good clinical utility in defining primary and secondary abnormalities in abnormal gait. The commonest DLS power abnormalities were the lack of A2 ankle power generation in DLS2 and this was associated with early onset of contralateral Gastrocnemius activity in DLS1. SLS abnormalities were characterized by co-activation of Tibialis Anterior and Gastrocnemius, Vastus and Hamstrings. The hip EMGs seem to be normal in a majority of the collections. The swing phase was also characterized by a largely normal pattern of power, EMG and range of movement. Moments were variable and were mostly used to define whether the abnormal muscles identified were eccentrically or concentrically active.

CHAPTER SIX

DISCUSSION

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METHODOLOGICAL ISSUES IN SLS/DLS ANALYSIS

This study was done on graphical data rather than subjects. Thus clinical data was not collected. It may be argued that this is a drawback, but as mentioned in previous chapters, gait analysis does not differentiate well between types of spastic or other pathological gaits, nor does it discriminate well between diplegia , hemiplegia and other geographic variables of disease (23). The aim of this study was to look at the biomechanical viability of the SLS/DLS gait analysis method and so biomechanical issues were of prime importance. Such a "non-clinical" approach has been undertaken in the past and several papers use mathematical modelling (rather than subjects) to analyse and test gait hypotheses (37, 40, 45).

This study was descriptive rather than statistical. The descriptive design was used because the purpose of this study is hypothesis generation. SLS/DLS analysis and its protocol in this format is being described, as far as known, for the first time. Comparing data at this stage is not appropriate, neither is using intervention, randomization or blinding. The use of the SLS/DLS analytical method was thought to produce gait pattern descriptions for each pair of twinned phases. Therefore, apart from establishing means and standard deviations for baseline data, no other statistical method was used.

The variability of the baseline data is a well known drawback, but also a physiological reality of gait analysis (50). While there is a statistical disadvantage to a large variability, in such a descriptive study, the larger the variability, the greater the opportunity to pick up unusual or instructive data. This approach is used in qualitative research and is referred to as critical case sampling technique. While this technique was not used in this study, the variability of data seen was dealt on a case by case issue e,g, the high PCI was evaluated and found to be because the biomechanical issue was because of contractures rather than spasticity or impaired voluntary control. So a large amount of energy was invested into producing a fairly normal gait pattern. Thus variability in an exploratory study will enhance rather than detract if each variable is individually analysed. Most of this data falls both outside and within the normal ranges of our gait lab providing a rich variability fro analysis.

IMPACT OF THE STUDY ON THE UNDERSTANDING OF SINGLE AND DOUBLE LIMB SUPPORT PATTERNS

The symmetricity of gait patterns seen in this study shows the first interesting feature of SLS/DLS phases. Ankle DLS2 and SLS and knee and ankle Swing data shows a high proportion of symmetry compared to other phases and joints. Less than half of the other joints and phases are symmetrical (Table 5.1). This shows that there is a definite difference in characteristics between DLS1, DLS2, SLS and Swing.

CHARACTERISTICS OF DOUBLE LIMB SUPPORT

The function of DLS is to provide stability. In DLS, both limbs are in contact with the ground and experience ground reaction forces at the same time. The detailed characteristics of power, EMG activity, range and moments are outlined in the results. The highlights and interpretation are discussed here.

The results of DLS showed a prominent absence of A2 power generation (Fig 5.2) without ipsilateral EMG abnormality (Fig 5.6). At the same time however, the contralateral Gastrocnemius activated abnormally early in DLS1 (Fig 5.5). Therefore this proves that the abnormalities of one limb can be caused by opposite limb abnormalities occurring at the same time.

Around 25-40% of the gait collections showed DLS1 power absorption (Fig 5.2). A large proportion of ipsilateral EMGs showed that Tibialis anterior, Vastus and hamstrings showed normal activity in DLS1 (Fig 5.6). A combination of absorption with normal EMGs again indicates that the effect is being caused by the opposite side.

In DLS1, the hip and knee were the primary power absorbing joints whereas in DLS2 the ankle was the primary absorbing joint. Hip DLS1 EMGs were normal whereas knee EMGs showed delayed onset in DLS1 (Figs. 5.2, 5.3). These knee delayed onset EMGs were associated with flexing moments and flexion range of movements indicating that DLS1 abnormalities are more due to impaired voluntary control rather than spasticity.

On the other hand, in DLS2, where the ankle was the primary absorbing joint, dorsiflexor moments and normal range of movement were associated with early and possibly co-contracting Gastrocnemius. This indicates that spasticity is involved in DLS2 power absorption at the ankle.

Thus the goal of the study, which was to assess the feasibility of SLS/DLS analysis was achieved for SLS as it was able to show conclusively that opposite limb muscles and biomechanics affected the joint.

It was also able to show that DLS1 absorption abnormalities are primarily at the knee and are probably due to impaired voluntary control.

However, it also indicated that DLS2 absorption abnormalities are primarily at the ankle and are probably due to spasticity and co-contraction.

Thus the stability function of double limb support phase is commonly affected by knee and ankle power absorption and this is due to a combination of impaired voluntary control at the knee and spasticity at the ankle in DLS.

CHARACTERISTICS OF SINGLE LIMB SUPPORT

The function of SLS-Swing phase is to provide mobility. The Power, EMG, range and moments of SLS are described in the results section. Their highlights and interpretation are discussed below.

In SLS-Swing, the highlight is that, unlike absorption abnormalities seen in DLS, generation abnormalities are noted in the hip (Fig 5.3). Generation abnormalities are associated with hip extensor moments and normal ranges (Fig 5.11) and these potentially reduce energy costs and therefore may not be as worrying to the clinician as absorption abnormalities. However, the associated EMG abnormalities are knee and ankle co-contractions (Fig 5.7). This indicates that the primary abnormality in SLS is spasticity but that this spasticity might actually be compensatory or beneficial (42).

An interesting finding in SLS/DLS analysis is the relative sparseness of abnormalities in swing. Even the absence of the Rectus Femoris peak in swing did not cause any power or range abnormalities. This may be because of the method of calculating forces in swing in the absence of ground reaction forces. Limb segment volume estimates may not be the most accurate way of doing this though it is an accepted method. But apart from methodological issues, the fact that swing is relatively spared suggests that either it is not a crucial part of SLS/DLS gait analysis or that there are other variables to be studied in swing e.g. swing limb clearance (5).

The hip too is relatively spared especially with regards to EMG abnormalities and range of movement. This brings to question whether this is the result of the body protecting the pelvis and hip with distal compensations ("proximal compensations for distal deviations") (2). If this is the case, correcting distal "deviations" without identifying whether they are compensating or not would result in increased energy cost or worsening gait patterns. The case study in the results is a case in point. All abnormal gait may not require correction. All spasticity may not require treatment. All abnormal gait patterns we see and parents or children complain of may actually help the child to continue to ambulate (42). Only observational gait analysis may be an insufficient tool in the management of abnormal gait. This study emphasizes the need for detailed biomechanical SLS/DLS analysis of walking before planning interventions in abnormal gait. It also emphasizes that the observed patterns are very different from the biomechanical patterns.

LIMITATIONS OF THE STUDY

1. Due to the descriptive nature of the study and the lack of quantitative and statistical analysis, description of SLS/DLS characteristic gait patterns may not be representative. In general, however, gait variability is an ongoing problem with gait analysis studies and data may either highly variable or too in-homogenous even to compare statistically (50).

2. No statistical methods to avoid bias were adopted in the methodology (randomisation, blinding) nor was the sample size calculated prior to the study due to lack of data from which power could be calculated.
3. Studying the ankle, hip and knee solely in the sagittal plane may lead to erroneous conclusions as the trunk and pelvis, transverse and coronal planes (pelvic drop or rotations, scissoring) could probably have a greater influence on abnormal gait (40).
4. Deeper muscles of importance like the Iliopsoas or Tibialis Posterior could not be studied with surface EMG electrodes. Others like Soleus have been reported to have opposing action to Gastrocnemius at the knee and hip and were not studied (43). Thus missing data may hide the truth of gait abnormality from us without needle EMGs.
5. Limitations of software and a full understanding to the EMG-force relationship precluded completely evaluating EMG waves especially with regards to force generated and direction of force which may have aided in segregating primary and secondary abnormalities (51).
6. There is only one force plate and so each collection is taken separately for each side. This creates a distance which is magnified by variability when comparing SLS/DLS.

Future research into SLS/DLS analysis needs to be done with interventional studies to evaluate the effects of interventions on the SLS/DLS hypothesis as shown in the case study.

SLS/DLS analysis with multiple simultaneous foot strikes will improve the quality of gait collection.

Collection and analysis of deeper muscle as well as a better understanding of EMG-force relationships need to be developed.

Mathematical models in current use need to include the effect of the opposite limb.

CHAPTER SEVEN

CONCLUSIONS

1. SLS/DLS analysis may be a useful technique to identify abnormalities caused by one limb upon the other at the same point in time and to differentiate between primary and secondary abnormalities of gait.
2. The stability function of double limb support phase is commonly affected by knee and ankle power absorption and this is due to a combination of impaired voluntary control at the knee and spasticity at the ankle in DLS.
3. DLS1 absorption abnormalities are primarily at the knee and are probably due to impaired voluntary control.
4. DLS2 absorption abnormalities are primarily at the ankle and are probably due to spasticity and co-contraction.
5. The primary abnormality in SLS is spasticity but this spasticity might actually be compensatory or beneficial.
6. Swing is characterized by mostly normal kinematic, EMG and kinetic activity.
7. The hip is relatively spared especially with regards to EMG and range of movement.
8. A larger study with randomisation and blinding if possible is needed to confirm the findings of this study. This study will help in calculation of power and appropriate sample size required.

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