Improving Rehabilitation Practice Through the Analysis of Musculoskeletal Muscle and Joint Forces during Motion

Master Thesis Project

ENGR 9700

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partial fulfilment of the requirements for the degree of Masters of Engineering(Biomedical) at
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Declaration

I certify that this work does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Abstract

Background: The child suffering from cerebral palsy shows abnormal gait. The condition of child who have abnormal gait will get worst if left untreated. The precise information about muscle and joint forces produced in children who have pathological gait is vital for describing the contribution of individual muscle in gait. This will help in developing new techniques to speed up their rehabilitation. Because the direct estimation of muscle forces in vivo is impractical. The joint kinematic and ground reaction force data from gait investigation trials are regularly utilized as part of musculoskeletal simulation to predict muscle forces.

Aim: The purpose of this project is to obtain muscle forces in cerebral palsy patients and compare these with forces obtained from the same muscles in the case of normal subjects.

Methods: An open source software known as opensim is used to estimate individual muscle forces by optimization technique. Three-dimensional computer model (included in opensim software) of the human musculoskeletal system is used to run simulations. The name of model used is gait2354. There are total 4 subjects with one trial each. One of them is normal and 3 have cerebral palsy. First of all, dynamic musculoskeletal model has its size readjusted to coordinate the subject's size and shape. The use of kinematic equations is made to obtain the joint torque that best reproduce the marker trajectories got from motion capture system. In the end static optimization is used to obtain individual muscle forces joint torque at all-time intervals.

Results: Graphs of Muscles forces at lower limbs during gait cycle is generated and comparison is done between normal gait and abnormal gait. Reasonably good correlation between calculated muscle forces and function of muscles is found. Muscle forces calculated in cerebral palsy patients were analysed by correlating them with gait abnormality seen in patient.

Conclusion: This study successfully identified the muscles responsible for abnormal gait pattern. Higher muscle forces are observed in children having abnormal gait due to cerebral palsy and because of this hip and knee joint reaction forces are also high. Similar finding are given by previous researches. Justification of results coming out of simulation is also done by considering the anatomic game plan of muscle in respect to the skeletal structure in actual human body. Considering everything, it is revealed that model used in this project could be used to get general idea about the muscle responsible for abnormal gait pattern in cerebral palsy child.

Future work: For further validation of results, the reliance on kinematics and ground reaction forces should have to be lessen by making use of forward dynamic optimisation which also enables to learn more, i.e. power, length, speed, actuation connections of the muscles, and with recorded electromyography signals during walking. Also, the generic parametrized model which comes with opensim requires modification for cerebral palsy subjects.

Chapter 1. Introduction

The child suffering from cerebral palsy shows abnormal gait, and is portrayed by abnormal joint angles during the process and time of gait. if the abnormal gait patterns are left untreated, the pain will start in their joints , deformities in bone will occur and there may be loss of autonomous gait. The Clinicians have always trying to keep their walking pattern normal through different rehabilitation procedure including surgery. The surgeon perform surgical procedure on the muscle which affect gait and it is hard to design a treatment strategy which will target muscles most likely to enhance dynamics of gait. Therefore, more research is required to know how individual muscles affect movement in an abnormal gait. Humans have built up walking pattern to accomplish forward movement while also supporting the weight of the body. Some researches (Anderson & Pandy 2003; Arnold et al. 2005; Kimmel & Schwartz 2006) have inspected how muscles move the joints and body during healthy walk. They have found that during moderate movement in the forward direction the muscles vastus and gluteus max provide the necessary support to the body during early stance phase of gait and in the late stance phase, it is the soleus muscle and the medial gastrocnemius muscle that are responsible for handling the weight of the body and promoting forward movement. (Anderson & Pandy 2003) showed that this role of these muscles are kept up over a scope of walking speed. (Hicks et al. 2008)broke down how the per-unit-force by individual muscles accelerates joints in leg during walking. In walking, the leg muscles satisfy three particular capacities, they create support by opposing the downward draw of gravity, they produce movement by progressing the body forward and they maintain mediolateral balance.

In the case of an abnormal gait the changes in the muscle initiation pattern and joint kinematics reveal how muscles affect movement of the joint and the body.

1.1 Objective of research project

The objective of this project was to estimate the muscle and joint forces in children having abnormal gait due to cerebral palsy . The forces generated by muscles which are important in support and progression of body were estimated. Joints reaction forces at hip and knee of each cerebral palsy subjects were calculated. The muscle and joint forces estimated in cerebral palsy subjects were compared with subject with unimpaired gait. It was understandable, that muscles and joint forces in cerebral palsy subjects would be different. Therefore, the relation between abnormal gait pattern and forces generated by muscle was tried to be established.

The generic musculoskeletal model available with opensim is used. It was tried to find that weather this model can be used for cerebral palsy child gait to get reliable results. There were no major modification done in model only it was scaled down on the basis of height and weight of patient.

Chapter 2. Literature review

Introduction

This chapter includes all the basic knowledge, concept required as foundation study for this project. First of all cerebral palsy is discussed in detail and different types pathological gait pattern are explained. In the next section, musculoskeletal structure is discussed from biomechanical viewpoint. The main focus in this section is on muscle. In the next section definition of human gait and explanation of gait cycle is given. After that, lower limb muscles are discussed briefly and in detail important lower limb muscles are explained in appendices. After that, the phasic activity of important lower limb during gait cycle is explained. In the end, explanation of musculoskeletal modelling and simulation is given.

2.1. Cerebral palsy

Cerebral means 'of the brain' and palsy means 'lack of muscle control'. A physical disability that affects movement and posture is known as cerebral palsy(Baxter et al. n.d.). This disorder is related to functioning of brain and nervous system. It is noticed that 2 to 2.5 children have cerebral palsy out of 1000 born. The advancement of medical technologies give rise to the survival of premature and smaller babies and due to this rate of children born with cerebral palsy is constant. The cerebral palsy could happen due to number of reason. It can happen due to defect in neural tube closure which is congenital cause. The natal and prenatal cause are premature birth, ischemic encephalopathy and cerebral bleeding. The postnatal causes are infections, trauma and metabolic encephalopathy. The treatment management does not depend on the cause of cerebral palsy.

Cerebral palsy can be classified anatomically according to motor deficit(table 2.1).

Monoplegic	One limb is affected
Diplegic	Both legs involved more than arms
Hemiplegic	Arms and legs on one side of body are affected
Triplegic	Lower limbs and one upper limb are affected
Quadriplegic	All four limbs are affected

Table 2.1(classification of cerebral palsy according to motor deficit)

Cerebral palsy can be further classified (motor element) as shown in table 2.2

Spastic	Stiff and tight Muscles and their movement may be observed as jerky and stiff. It is most common form of motor element i.e. 70 to 80 % individuals who have movement problems due cerebral palsy comes under this category. It happens due to problems in corticospinal or pyramidal tracts. Pyramidal tract lesions in a brain which is not completely developed causes spasticity. The spasticity can be judged from symptoms like joint subluxations, contractures, fatigue, balance disorders, loss of dexterity and coordination.

Dyskinetic	Variable movement of muscles which is involuntary or out control especially when a person tries to move. Dyskinetic movements can be of three types i.e. dystonia, athetosis, chorea.
Ataxic	Ataxic means without order or uncoordinated movement of muscles. It is least common one
Mixed	Combination of any of the above or all

Table 2.2(classification of cerebral palsy according to motor element)

2.2. Pathological gait in children with cerebral palsy and common gait patterns.

The attained musculoskeletal pathology generated due to the brain lesion causes pathological gait or gait deviation. Phasic ally incorrect activity of muscle, spasticity of muscle and contractures over the joints are some musculoskeletal disorders happening due to brain lesions. In case of contractures over the joint, abnormal behaviour of one main joint in lower part of body can effect functioning of the other joints. It is also true that child with cerebral palsy suffers modification in gait as they grow(Bell et al. 2002). Next is Common gait patterns in children with cerebral palsy

Stiff knee gait- It is the most common gait abnormality seen children with cerebral palsy. Stiff knee gait can be judged from diminished knee motion and delayed peak knee flexion during the swing phase of gait cycle as shown in fig. 2.3(Goldberg et al. 2003).

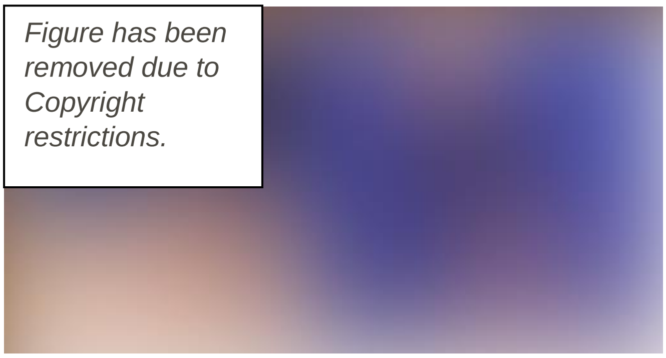

Figure 2.3, left leg is showing stiff knee from pre swing to initial swing(photograph courtessy of centre for gait and movement analysis[Children Hospital, Colarado])

Due to inadequate toe clearance, children who have stiff knee gait perform inefficient compensatory movements or trip frequently while walking. Potential causes of stiff knee gait are increased vasti and decreased iliopsoas activity as identified in (Goldberg et al. 2006). Additionally, abnormally prolonged activity of rectus femoris during early swing could affect flexion of knee. But rectus femoris has limited effect. To improve stiff knee gait a common surgical intervention is distal transfer of the rectus femoris. The purpose of this surgery is to decrease the ability of rectus femoris to extend knee while it can still flex hip. In this way, more flexion of knee is expected after this surgery.

Equines foot- The word equines in itself describes the condition of insufficient ankle dorsiflexion which leads to the excessive plantar flexion due to the spasticity of the gastro soleus, tibialis posterior(Tugui & Antonescu 2013). In this hip is in extension, the knee position remains in neutral state as a result the child walks on his tip toes(fig. 2.4).

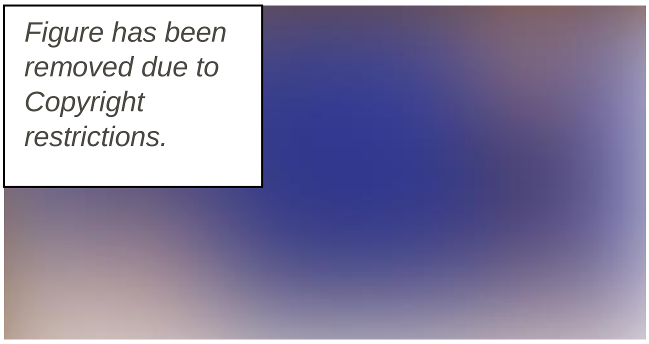

Figure 2.4, Equinus gait, (photograph courtessy of centre for gait and movement analysis[Children Hospital, Colarado])

The diagnosis of equines involves measuring the dorsiflexion angle of the foot. If the foot is perpendicular to the leg and put through a range of motion where the foot cannot dorsiflex (move upward) more than 10 degrees this is thought of as an equines deformity. Treatment procedure depends upon the type of the muscles which involves surgical methods such as lengthening of Achilles tendon as well as providing dosage of botulinum toxin, kinetic therapy and the use of AFO (ankle foot orthosis: a device which is designed to support the foot and ankle intended to control motion and proper alignment).

Crouch gait- Crouch gait include too much flexion of knees and hips throughout the stance phase of gait cycle as shown in fig.2.5(Hicks et al. 2008).

Figure 2.5, Crouch gait, (photo courtessy of centre for gait and movement analysis[Children Hospital, Colarado])

This abnormal walking pattern is an issue because during walking it intensely increases the energy requirements, patient feel difficulty in foot clearance during swing phase and also patellofemoral force increases. If it left untreated the crouch gait get worse and can cause intense pain in knee and variation in joint mechanics of patellofemoral joint. It is difficult to treat patient with crouch gait because most of the time the biomechanical reasons of too much flexion of knee and hip are unknown. In some children with crouch gait it is supposed that spasticity of hamstrings bounds extension of knee and to treat those patients' hamstrings are surgically lengthened. In other children, poor strength of ankle plantar flexor muscle in producing planter flexion at ankle is considered responsible for crouch gait and for them special ankle foot orthoses are suggested. One reason which is getting more attention is week hip and knee extension movement due to extensor muscles. It is also hypothesized that foot, femur and tibial mal-rotation, tight hip flexors can also contribute to crouch gait.

Jump gait- This gait disorder is a combination of equines, knee flexion and hip flexion. The muscle involved in this deformity are gastrocnemius, hamstring, hip adductors(Lin et al. 2000). It is called jump gait because child jumps in mid and late stance phase with correction of the knee angle to normal or close to normal knee extension in mid stance and late stance. This happens due hamstrings muscles overactivity during late swing to early stance which produces increased flexion movement at knee and overactivity of ankle plantar flexor muscle during mid to late stance which produces knee extension. Due to the mild shortening and hardening of hip flexors and hip adductors exaggeration hip flexion is their all through the gait. Due to increase in tone of hamstrings muscle without contracture full extension of knee not happen sometime. Treatments involve chemo denervation in which botulinum neurotoxin A injection is given to hamstrings which are spastic but without contracture. There are different soft tissue lengthens surgeries performed to treat jump gait deformity. These lengthening of medial hamstrings alone sometime in combination with semitendinosus transfer.

Scissor gait – This gait can be recognized by toes pointing inward and knee and thighs hitting or in extreme case even crossing each other (fig.2.6).

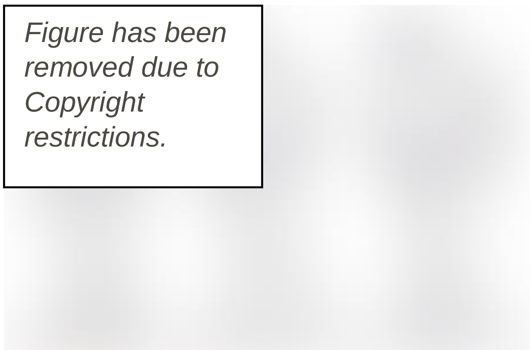

Figure 2.6,(photo courtesy- Coroflot, New York)

Tight adductors are considered responsible for the production of adduction movement at legs.

2.3. Biomechanics of Musculoskeletal Structure

Biomechanically, muscle is thought to be an actuator, which gives drive and energy to the movement and equalization of the musculoskeletal structures(Brunner & Rutz 2013). The anatomic game plan of muscle in respect to the skeletal structure decides mechanical conduct and capacity of muscle. The mobilization of the muscle and the extent of the muscle power applied for a given instant are subject to muscle physiology and the mechanical course of action of the musculoskeletal framework. Muscle physiology directs the capacity of the muscle under static and dynamic conditions(An et al. 1989). Origin of most muscles is proximally in wide connection to either fascial sheets or to the film on the surface of bone known as periosteum. Muscles inserts at the distal end of bone with thinner tendinous attachment. It is considered that insertion is usually moving and origin is immobile for example the brachialis muscle during elbow flexion. It may be not true for all for example during planter flexion of ankle to raise the heel of subject the muscle involved are soleus and gastrocnemius neither end of the muscle is purely immobile.

A liner force at distance from centre of the joint is applied by muscle which produces movement of joint. This is known as moment or torque. Moment or torque is calculated as

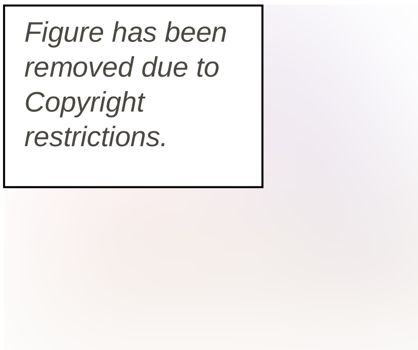

Figure 2.7 muscle moment

T= F x d
T = torque or moment
F = force perpendicular to lever/moment arm
d = length of lever/ moment arm (distance from force to centre of rotation).
At each given joint angle the muscle ability to generate force is different because with movement of joint, the length of muscle crossing the joint changes (see Figure 2.8). The viable lever arm of the muscle likewise changes(Hoy et al. 1990).

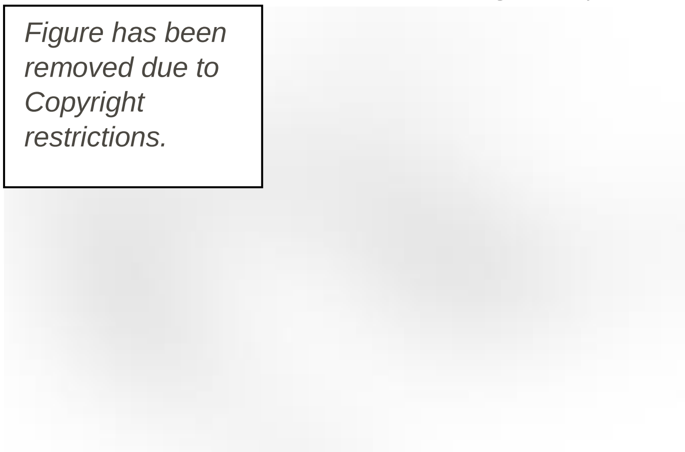

Figure 2.8, change in lever arm as joint angle changes (muscle physiology, UC San Diego)

The centre of rotation of joint changes in special joints like knee. This feature of joint is an addition to further variation in the moment produced by muscle. It is seen that muscle cannot generate maximum forces all through the whole range of motion of joint and also it is possible that muscle is not generating maximum force during midrange of muscle motion. Moment production investigation on animals and humans have demonstrated that maximum moment arm and maximal generation of force by muscle may not occur at same angle(Moss 1979). Rather maximization of muscle force generation occurs at the extreme end of the range of motion in many cases. Therefore, both muscle forces and moment arm changes constantly during normal rotation of joint. The lever arm and excursion of the muscle both decides the degree of joint movement. It's the fibre length of the muscle which decides the excursion a muscle can produce. Suppose the fibre length of two muscles is same, the muscle which have smaller lever arm will produce more rotation of joint but it will require more force to do so(fig. 2.9).

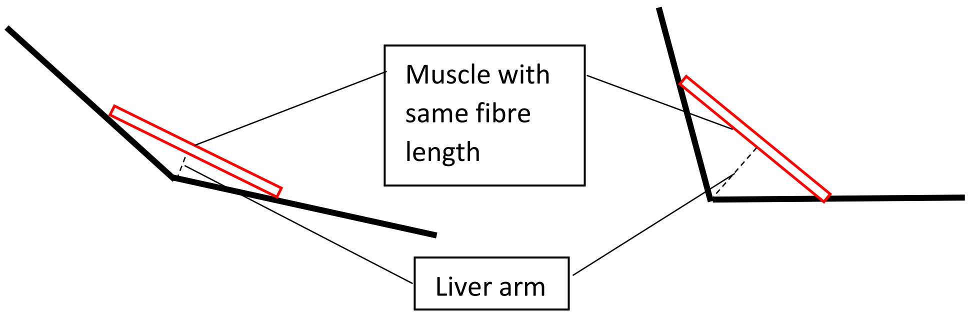

Figure 2.9, lever arm and joint rotation

As a rule, a muscle can cross a few joints, and there can be various muscles spreading over one given joint. Mechanism of Muscles that span two joints is different. For example, on each end of hamstrings muscles there are continually varying two different lever arms as it acts on different joints. Additionally, length-tension properties at one end of two joint muscle could be affected by changes in lever arm at other end as it changes the length of muscle. In human walking muscle that spans two muscles are important because transfer of energy between two joints is possible with this configuration. Additionally, it is not necessary that joint motion can only be affected by the muscle which is intuitive. A muscle can produce movement at different joint even if it is spans a different joint. Not only this, the muscle which crosses two joint can compete with their applied moment. For example, it is shown in many studies that muscle moment produced at other joints in leg influence the motion of knee. One another important concept in biomechanics of muscles is work. Concentrically contracting muscle preforms positive work. An example of positive work performed is of biceps brachii, when the elbow is flexing to lift some weight. When muscle eccentrically contract it perform negative work. For example, consider hip extensor muscle gluteus maximus. During early stance phase of gait cycle, it eccentrically contracts to resist hip flexion movement produced by ground reaction forces acting on foot. It is to be noted that from mechanics these definition of work is coming; these can be compared with response of spring when weight acts on it. Also, these are not metabolic terms because whether the work performed is positive or negative contraction of muscle consumes energy. As eccentric contraction requires less motor unit activity than concentric therefore electromyography activity is less in eccentric. Isometric or eccentric activity is more during human walking which improves energy efficiency. During walking, positive work is performed by muscles in progression of body centre of mass and negative is performed to support body vertically.

In view of inflexible body mechanics, when force and moment connected to an item are equalised the article will keep up its balance position. Nonetheless, if the forces and moment are uneven, there will be a related motion i.e. translation and revolution. Mathematically, such cooperation can be portrayed by the equilibrium equations while doing free-body examination(Okuda et al. 1987). From this mechanical perspective, the musculoskeletal framework can be considered as a gathering of unbending fragments interconnected at the joints. The muscles serve as actuators giving strengths to move the portions and adjust the joint. Along these lines, it can be said that the role of joint stabiliser and that of a segment mover is taken up by the muscle. The capacity of mover and stabilizer can be portrayed separately based on moment arm and line of activity considered in the equilibrium equations.

2.4. Human Gait

Human Gait is characterized as bipedal, biphasic forward drive of centre of gravity of the human body. Different segments of body move during gait in such a way that least amount of energy is spent. The mechanics of human gait include synchronization of the skeletal, neurological and strong frameworks of the human body.

2.4.1. Gait cycle

The time frame between any two exact same moments during walking is called gait cycle. The gait cycle begun when one foot strikes the ground and ends when same foot again contacts the ground.

Figure has been removed due to Copyright restrictions.

Figure 2.10 Human gait(Uustal & Bearga 2002)

Gait cycle is divided into two main parts and they are stance and swing (see Figure 2.3). The stance phase begins with heel strike and ends at toe off. Stance phase contains 60% of total gait cycle. However, the swing phase begins at toe off and ends at the next heel strike. Swing phase covers 40 % of total gait cycle.

2.5. Important lower limb muscles used in gait

Lower limb muscles can be divided into five groups i.e. muscles of the foot, muscles of the gluteal region, muscles of the leg, muscles of the thigh and the fascia lata.

Gluteal region

Starting with gluteal region, anatomically it is located at femur proximal end, posterior to pelvic girdle. It is mainly responsible for moving lower limb at hip joint. The gluteal region muscles mainly have two groups . One of them is hip extensors and superficial abductors and other is deep lateral rotators. Hip Extensors and superficial abductors group comprises the gluteus medius, gluteus maximus, gluteus minimus and tensor fascia lata. They are large muscles which perform extension and abduction at the femur. These muscles are very important in gait. The deep lateral rotators group comprises gemellus superior, gemellus inferior, piriformis and obturator internus. These are smaller muscles which rotates the femur laterally.

Muscles of thigh

The muscles of thigh can be divided into three sections i.e. anterior , medial and posterior. The main muscles at the anterior of thigh are the quadriceps femoris, pectineus and Sartorius. Psoas which is a end part of iliopsoas muscle also lie in the anterior section. The quadriceps and iliopsoas are big muscles and can produce extensive deviation in gait. All the muscles in the medial section of thigh are together called as the adductors of hip. In this group there are five muscles i.e. adductor magnus, adductor longus, adductor brevis, obturator and gracilis. In the posterior section of the thigh are the semitendinosus, biceps femoris and semimembranosus.

Muscles of leg

In the anterior section of the leg there are four muscles these are extensor hallucis longus, extensor digitorum longus, fibularis tertius and tibialis anterior. All of them perform dorsiflexion and inversion of the ankle joint. Tibialis anterior is main muscle which is consider in gait cycle. In the posterior section of the leg main muscle are soleus and gastrocnemius. In the lateral section of leg there are two muscles, brevis and the fibularis longus.

Muscles of the foot

The muscles of the foot, they are extrinsic and intrinsic muscles in foot. The extrinsic muscles ascend from lateral, posterior and anterior leg sections. Action performed by them at foot are inversion, eversion, plantarflexion and dorsiflexion. Whereas intrinsic muscles are present within the foot and they produce fine motor movements of digits. The insertion, origin and function of important lower limb muscles used during human gait are given in appendix. The muscles are pictorial presented and highlighted. The insertion and origin points are also highlighted.

2.6. Individual muscle contribution in supporting and progression of body during gait cycle

During stance and swing phase of gait cycle many muscles are active. The phasic contraction of muscles is important in producing normal walk (Arnadottir et al. 2011). In precise, orchestrated fashion muscles contract and relax during normal walking (Pandy et al. 2010). Normal walking is only possible through exact sequence of muscle recruitment (Table 2.3).

Heel Strike | Foot Flat | Contralateral toe off | Heel off | Toe off | accerleration | deceleration

	INTIAL CONTACT	LOADING RESPONSE	MID STANCE	TERMINAL STANCE	PRE-SWING	INITIAL SWING	MID SWING	TERMINAL SWING
	STANCE PHASE 60%					SWING PHASE 40%		
% of total phase	0-2%	0-10%	10-30%	30-50%	50-60%	60-73%	73-87%	87-100%
G. Max.	Active	Active	Inactive	Inactive	Inactive	Inactive	Inactive	Inactive
G. Med.	Active	Active	Active	Active	Inactive	Inactive	Inactive	Inactive
Iliopsoas	Inactive	Inactive	Inactive	Active	Active	Active	Inactive	Inactive
Hamstring	Active	Active	Inactive	Inactive	Inactive	Active	Active	Active
Gas	Inactive	Inactive	Inactive	Active	Active	Inactive	Inactive	Inactive
Soleus	Inactive	Inactive	Active	Active	Active	Inactive	Inactive	Inactive
Tib. Ant.	Active	Inactive	Inactive	Inactive	Active	Active	Active	Inactive
Vasti.	Inactive	Active	Active	Inactive	Inactive	Inactive	Inactive	Inactive
R. Fem.	Inactive	Inactive	Inactive	Inactive	Active	Inactive	Inactive	Inactive

Table 2.3, phasic activity of muscles during gait cycle (Kadaba et al. 1985)

The gait cycle starts with initial contact in which heel strikes occurs. To stabilize and position the knee in space the simultaneous activity of knee extensor and flexor occurs. The knee flexors which are active during this time are hamstring muscles. However, the knee extension moment is generated through deceleration of thigh happening due to hip extensor contraction.

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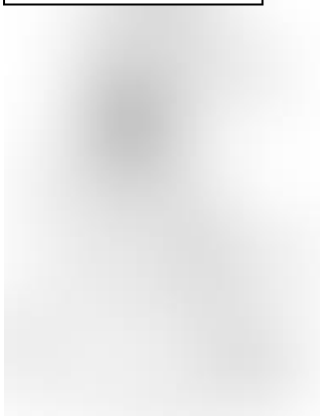

Figure 2.11(Gage 1990)

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Figure 2.12(Gage 1990)

At the same time, the ankle dorsiflexor muscles gets active Just after heel strike (Figure 2.11) to gradually 'ease down' the foot and keep it from slapping down on the floor(Hamner et al. 2010). The main ankle dorsiflexor muscle is tibialis anterior. The next phase of gait cycle is loading response (Figure 2.12) and loading response begins just after heel strike and ends before mid-stance. During loading response foot flat occurs. From foot-flat to just after contralateral toe-off(shown in Table 2.3) the support against vertical ground reaction forces is provided mainly by vasti, gluteus maximus and gluteus medias(Arnold et al. 2005). Note that, hip and knee both accelerates towards flexion due to the ground reaction forces. To stop the flexion of these joints the main muscle which are acting are gluteus maximus and vasti.

Therefore, the first maximum (maximal weight acceptance) observed in vertical ground reaction force (Figure 2.13) is formed due to activity of these three muscle group. Although, passive resistance of joints and bones are also assisting against gravity (Marasovič et al. 2009).

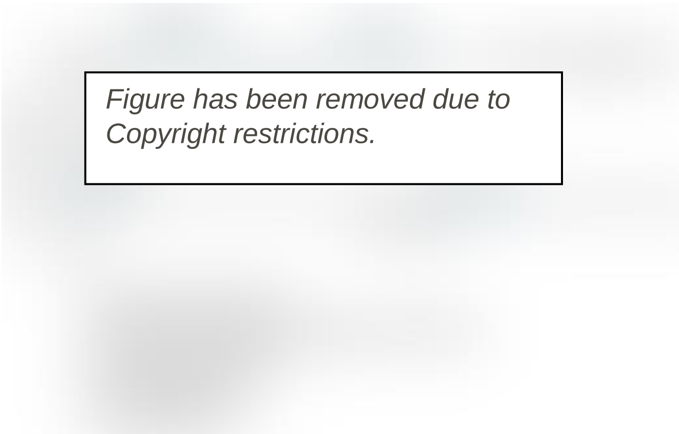

Figure 2.13, vertical ground reaction forces

Gluteus medias stay active and support body throughout mid-stance to terminal stance (table 2.3) and it works to stabilize the pelvis. The knee extension is aided by plantarflexion of the ankle. During midstance the centre of gravity of body is maximum and is body is going forward due to its momentum.

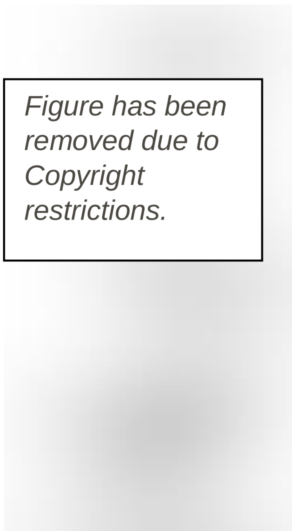

Figure 2.14(Gage 1990)

During mid stance, As the knee remains extended the body mass falls forward in the direction of walking progression. This forward falling of body is protected by lengthening contraction of the soleus muscle (an ankle planter flexor) which keeps the forefoot pressed against the floor (Figure 2.14). Also, soleus creates force couple or linkage which allow the knee to remain extended without quadriceps.

The calf muscles which work as ankle planter flexors. They also, push body forward during late(terminal) stance (Figure 2.15)(Liu et al. 2006). Soleus and gastrocnemius are the main planter flexors of ankle and are main muscles responsible for the second maximum observed in the vertical ground reaction forces (Figure 2.13).

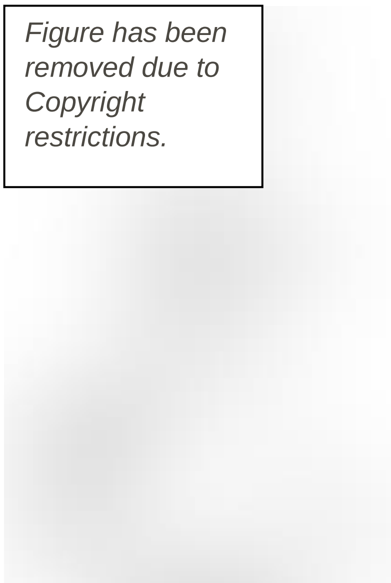

Figure 2.15(Gage 1990)

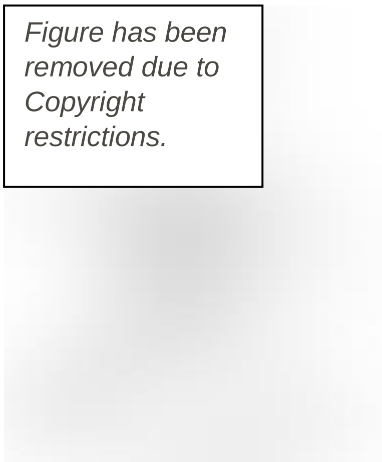

Figure 2.16(Gage 1990)

Preswing (Figure 2.16) starts when the contralateral limb is on floor and starts bearing load. In this phase of gait cycle all the above discussed muscles are inactive and hip flexors i.e. iliopsoas, rectus femoris starts lifting of the limb to swing it forward in air(Andersson et al. 1997). Iliopsoas is muscle which get active in late stance and it deaccelerate the extension of hip and accelerates hip towards flexion till initial swing(Nene et al. 1999). The activity of muscles in preswing phase sets the condition of mostly passive events in following part of gait cycle. In other words, limb acts like passive pendulum after preswing phase. There is end in activity of rectus femoris in initial swing phase but iliopsoas stays active a bit more.

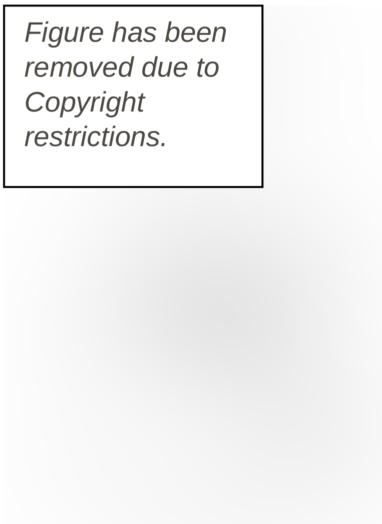

Figure 2.17(Gage 1990)

The ankle which was planter flexed at preswing is dorsiflexed with contraction of tibialis anterior muscle and this allow the foot to clear the floor (Figure 2.17). The passive pendulum action of leg continues during midswing and foot clearance is also continued by anterior tibialis muscle. During terminal swing the contraction of the hamstrings starts active deceleration of the limb. The hip flexion and knee extension is slowed down efficiently(Ellis et al. 2014).

2.7. Musculoskeletal modelling and simulation

2.7.1. Introduction

Musculoskeletal modelling could be used to obtain clinically relevant information on the function of skeletal muscles which is otherwise not possible to obtain through experiments alone(Delp et al. 1990). Modelling and simulation could be used to identify which muscles are causing abnormal gait. Surgical intervention on muscle which is causing abnormal gait could be than done to improve gait. In this way in patients with neurological and musculoskeletal impairments by knowing the cause and effect relationships, rehabilitation process can be improved and also treatment cost can be reduced.

Direct measurement of important variables like muscle forces is limited to minimally invasive measurements and that too is only possible for some superficial muscles. The basic principle on which non-invasive methods rely on are ground reaction forces and skeletal movement produced by muscles. But, these variables have no information for single muscle. In gait analysis Inverse dynamics technique is used on computational models of linked body segments to calculate joint torques (Bontrager 1998). This torque represents all muscles crossing a joint i.e. their resultant action on joint. As the muscles are not represented while using inverse dynamics tool in gait analysis therefore there is no information on how muscles shares load during walking. There is no estimate of force produce by individual muscle. Individual forces produce by muscles can be estimated with representation of both muscles and skeletal in computational models (Heintz 2006). In conjunction with non-invasive measurements these types of musculoskeletal models could be implemented in number of ways to estimate muscle forces.

2.7.2. Equation used relating muscle forces with motion

The combination of musculoskeletal models, movement data and optimization method is done to estimate muscle forces (Erdemir et al. 2007). There is equation used for musculoskeletal model which relates the movement and muscle forces(Anderson & Pandy 2001)

$$\boldsymbol{M(q)q'' + C(q)(q')^2 + G(q) + R(q)Fmt + E(q,q') = 0} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \boldsymbol{eq.1}$$

In this equation ***q, q', q''*** are vectors representing joint angle, angular Velocities and angular accelerations, respectively. ***M(q)*** represent the mass matrix of system. ***M(q)q''*** is vector representing inertial torques and forces, ***C(q)(q')***^{2} is a vector representing Coriolis and centrifugal torques and forces*,* ***G(q)*** are vectors representing gravitational torques and forces. Muscle moment arms are represented by ***R(q)Fmt*** is vector representing musculotendon forces. ***R(q)Fmt*** is a vector represent torques produced musculotendinous structure. External forces and torques applied on the model are represented by ***E(q,q')****.* The number muscle forces which are unknown are always more than number of equations therefore the system is often redundant. For the estimation of muscle forces, muscles should be combined which will reduce number of muscles or methods based on optimization criterion could be used (Pierrynowski & Morrison 1985). The reduction technique is used in gait analysis to calculate muscular torque produced at each joint. In this case the generalized equations of system are reduced and muscular loading is corresponded to its degree of freedom (Otten 2003).

2.7.3. Coupling of muscle and skeleton

The relative moment arm as the joint moves is defined by muscles insertion and origin sites. The product of muscle moment arm and force produced by same muscle gives the magnitude of muscle force contributing to resultant joint torque which rotates joint. The magnitude of muscle force contributing to resultant joint torque is also known as moment. By definition moment arm is perpendicular distance between the axis of rotation of joint and line of action of muscle. But this distance depends on joint angle as described in eq. 1.
Relation between moment arm, length of muscle and joint angle is given using the virtual work principle(An et al. 1984).

$$\boldsymbol{Mij(q) = -\frac{dLj(q)}{dqi}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \boldsymbol{eq.2}$$

Where ***Mij(q)*** is moment arm of muscle j with respect to joint axis i. ***Lj(q)*** is the length of muscle from origin to insertion which depends on all joint angles q. Therefore, insertion and origin of muscle in musculoskeletal model should be exact and anatomical correct for the estimation of muscle forces. Also 3-dimensional path followed by muscle as the skeleton moves should be described properly (Delp & Loan 1995).

2.7.4. Modelling of muscle

Muscle have complex and nonlinear properties in generation of the force. (Zajac 1989) has given the most common hill type muscle model in simple form(Figure 2.18) It is a dimensionless muscle model with lumped-parameters for the purpose of simplicity. It can represent many muscles with different architectures. Tendon in series with hill-type contractile element represent each of muscle-tendon unit used in musculoskeletal model. There are normally more than 50 muscle-tendon unit actuating a complex musculoskeletal model. There are three components present in a muscle tendon unit: a contractile element(CE), parallel element(PE) representing muscle and series element(SE) representing tendon.

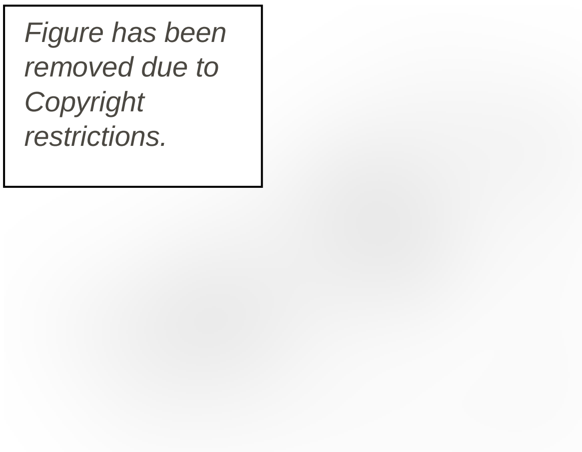

Figure 2.18(Erdemir et al. 2007)*, Hill type muscle model*

There are three things on which magnitude of the muscle forces depends. The activation dynamics of muscle (activation level), normalized length of muscle, the normalized velocity of muscle unit. Contractile element is represented by active tension generated by muscle and whereas parallel element and tendon are represented by passive tension. Tension which they can generate as the length of muscle varies is given in Figure 2.19

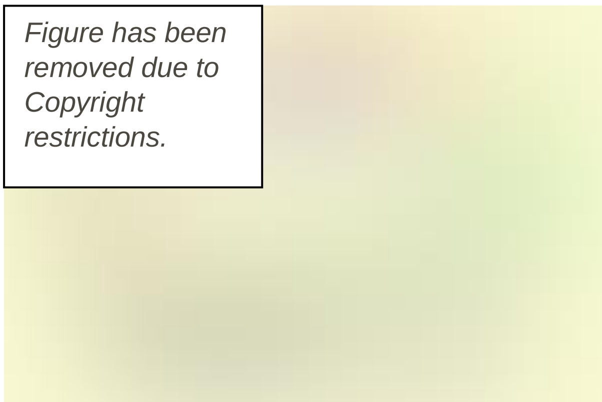

Figure 2.19 (Chai, 2002),length tension curve for muscle

Characterization of each muscle is done by defining its parameters i.e. maximum isometric force, tendon slack length, optimal fibre length, maximum contraction and pen nation angle. Maximum force a muscle can produce is defined by these all these inherent properties muscle model.

2.7.5. Muscle force estimation (inverse dynamics based static optimization)

From almost three decades' muscle forces are estimated by using motion data with inverse dynamics based static optimization (Tsirakos et al. 1997). By using joint kinematics and ground reaction forces joint torques are calculated.

Muscular joint torques at each instant of motion can be calculated by rearranging the eq. 1

$$\boldsymbol{Tmt} = (\boldsymbol{R}(\boldsymbol{q})\boldsymbol{Fmt}) = \boldsymbol{M}(\boldsymbol{q})\boldsymbol{q}'' + \boldsymbol{C}(\boldsymbol{q})(\boldsymbol{q}')\mathbf{2} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{E}(\boldsymbol{q},\boldsymbol{q}') \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{eq}.\mathbf{3}$$

Equation 3 represents system dynamics and it is used very less instead of this joint torques are calculated using single segment equation of motion(Winter 2009). After that static optimization technique is used to estimate individual muscle forces. In this the best set of muscle forces that produces net joint moments at each instant of time is determined. It is made sure that these muscle forces optimize a performance criterion and do not breach limits of muscle. This performance criterion is actually used to copy the function of neural control system.

From the following two condition of muscle activation to force generation one is used in static optimization.

1. Muscle as Ideal force generators:

$${}^{n}\Sigma_{m=1}(a_m F_m{}^{0})\, r_{m,j} = M_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{eq.4}$$

2. Muscle constrained by properties like velocity-force-length:

$${}^{n}\Sigma_{m=1}[a_m f(F_m{}^{0}, l_m, v_m)]\, r_{m,j} = M_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{eq. 5}$$

while minimization an objective/cost function

$$J = {}^{n}\Sigma_{m=1}(a_m)^{P} = {}^{n}\Sigma_{m=1}(F_m/PCSA_m)^{3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{eq. 6}$$

Here, ***n***= number of muscles model contains

a_m = muscle m activation level during discrete step of time

$F_m{}^{0}$= maximum isometric force

l_m = length of muscle

v_m = shortening velocity of muscle

$f(F_m{}^{0},l_m,v)$ = function representing maximum isometric force, length, velocity of muscle

$r_{m,j}$ = moment arm of muscle across joint axis j.

M_j = Moment acting across joint axis j.

p = constant defined by user.

F_m = *Muscle force*

$PCSA_m$= *Physical cross-sectional area of the muscle*

The redundant muscular force system is solved by using different optimization tactics. The main differences are in the choice of solution methodology and in the setup of cost function. The performance criteria or cost/objective function works to minimize the muscular system activation.

Eq. 6 - For each 1% period of gait cycle, the group of muscle forces that minimizes the objective/cost function are found by computer.

Eq. 4 - Predicted muscle forces are limited by constrain i.e. it should not violate upper bound or muscle force limit (maximum isometric force) while optimizing performance criterion.
Eq. 5 - This eq. also consider the force-length, force-velocity relationship in addition conditions described in eq.6, eq. 4.

Summary

To sum up, I have gone through the literature as shown in references and appendices which is briefly explained in literature review chapter under different section. I have traced the relevant literature through different sources like internet, library, labs, hospitals. The relevant literature is briefly summarised as follows. Cerebral palsy is disorder related to brain, neurological system and muscle. Cerebral palsy can be classified on the basis of anatomy and also according to motor element involved. In the next section the different types of pathological gait are discussed. Different types of pathological gait discussed are stiff knee gait, equines, scissor gait, crouch gait, jump gait. Biomechanically, function of muscle is to stabilize joint and also to move segment. The force applied by them depends on the anatomic game plan of muscle in respect to bone. The joint movement produce by muscle not only depends on excursion produce by its muscle fibres but also on lever arm of muscle. The muscle crosses one joint can produce moment at joint which they do not cross by making a muscle couple with another muscle. The important lower limb muscles which significantly affect gait are gluteal muscles, quadriceps femoris, hamstrings, calf muscles and iliopsoas. During loading response i.e. from foot flat to contralateral toe off the support against vertical ground reaction forces is provided by gluteal muscles at hip. Whereas at same time, vasti which is a part of quadriceps deaccelerates the knee as it get flexed due vertical ground reaction forces. Gluteus medias stay active throughout the stance phase as it works to stabilize the pelvis. During mid stance, with extended knee the forward fall of body is protected by the soleus muscle which keeps the forefoot pressed. Soleus and gastrocnemius which are ankle planter flexor. They pushes body forward during late(terminal) stance phase. During pre-swing phase iliopsoas, rectus femoris gets active to lift limb to swing it. Direct measurement of important variables like muscle forces is only possible through musculoskeletal modelling. In gait analysis Inverse dynamics technique is used on computational models of linked body segments to calculate joint torques (Bontrager 1998). As the muscles are not represented while using inverse dynamics tool in gait analysis therefore there is no information on how muscles shares load during walking. Individual forces produce by muscles can be estimated with representation of both muscles and skeletal in computational models. The musculoskeletal models are simulated with movement data and optimization methods are then used to estimate muscle forces. During coupling of muscle and skeleton in musculoskeletal modelling , the relative moment arm as the joint moves is defined by muscles insertion and origin sites. Modelling of muscle is also done as muscle have complex and nonlinear properties in generation of the force. Hill type muscle model is most commonly used in musculoskeletal modelling.

Chapter 3. Method used in research project(3d gait analysis to individual muscle force estimation using opensim)

3.1. Overview

In this project joint forces and individual muscle forces were estimated by running 3d musculoskeletal model using synchronous recordings of motion kinematics and ground reaction forces of human gait. The motion kinematics and ground reaction forces data was collected through 3d gait analysis. The software used to run simulation of musculoskeletal model was opensim. In matched anthropometry model the marker trajectories and ground reaction forces from gait analysis as an input are used.

3.2. 3d gait analysis data from Gait lab

The DE identified 3d gait analysis data of cerebral palsy patients was provided by Repatriation General Hospital at Daws park. Ethics approval for use of data was taken from (SA HREC) Southern Adelaide Human Research Ethics Committee. Gait lab at Repatriation hospital have 8x Vicon MX3 3D motion capture cameras and 4x AMTI OR6-7 Force Plates. Details of retro-reflective marker were given by (Baker, 2013). Video information were examined at 100 Hz whereas analog force plates were recorded at 1000 Hz. All analyses were led in the 4Th generation rehabilitation clinic at Repatriation General Hospital. The data from gait lab was available in .c3d format which was not compatible with Opensim. C3d (Coordinate 3D) files are subset of a more general (AD Tech) File format designed by Andrew Dains to hold data and their associated parameters within single file. The pre-processing of data was required to convert into .trc format and .mot format. The *.trc* (Track Row Column) file format was created by Motion Analysis Corporation to specify the positions of markers placed on a subject at different times during a motion capture trial. The .mot file is used to represent the joint angles and ground reaction forces. In this project MotoNMS toolbox was used to convert C3D file (Gait lab data) into .trc and .mot (opensim compatible format). MotoNMS toolbox was implemented in matlab(Figure 3.1).

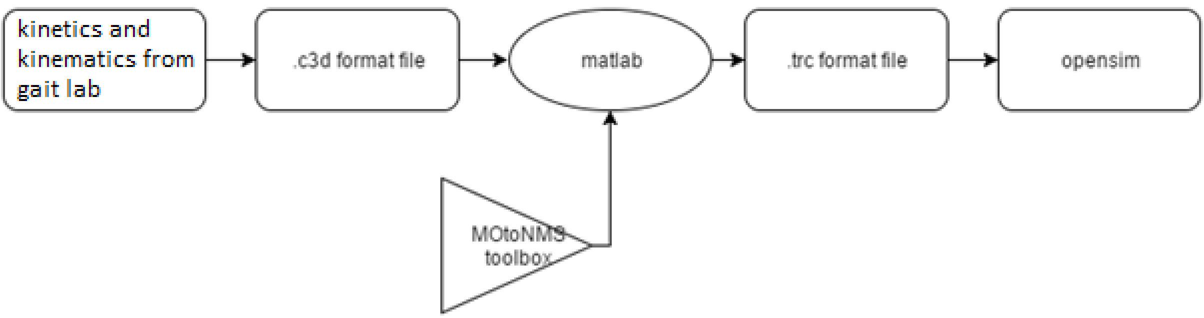

Figure 3.1, 3d gait analysis to individual muscle forces

Anthropometric measures of cerebral palsy subjects

Subject	Height(cm)	Weight(Kg)	CP type
1	131	46.2	diplegic
2	150	94.2	diplegic
3	140	81.9	diplegic

Table 3.1

The experimental data of normal subject used was collected as part of the study(Taylor et al. 2012). The height of patient was 180cm and weight was 72 kg

3.3. Simulation of Musculoskeletal Model in opensim

Opensim is a freely available, user extensible software system that lets users develop models of musculoskeletal structures and create dynamic simulations of movement. There are number of tools available in opensim which can be used to estimate individual muscle and joint forces from running model. A 3D muscle-actuated model was used in opensim with 23 degree of freedom. The model was represented by 54 musculo-tendon units. Every leg was represented by 24 muscles. The skeleton was articulated to as a 10-segmet, 23 DOF linkage. The head, arms, and middle were displayed as a solitary inflexible body. They were articulated with the pelvis by means of a ball and socket back joint. The lower part has 7 exact-body sections: pelvis, tibia/fibula, femur, toes, patella and foot (it incorporates the navicular, calcaneus, cuboid, metatarsals, cuneiforms). Hip is represented by a ball-socket joint. Knee joint is represented with coupled translation of a planer joint. Ankle is represented with a revolute joint. The model was built by Ajay Seth, Scott L. Delp and Frank C. Anderson from Stanford University and Darryl Thelen from University of Wisconsin-Madison. The model contains lower portion of joint definitions incorporated from (Delp et al. 1990) and a planar knee model from (Yamaguchi & Zajac 1989). Anthropometry and low back joint received from (Anderson & Pandy 2001).

There are three steps to create dynamic simulation of model and to estimate forces generated in that simulation. In step 1, The model was altered to anthropometric measures of subjects utilizing scale tool. Subject-particular model was made by scaling a bland musculoskeletal model with the goal that it coordinates the anthropometry of a specific person. This was accomplished by using opensim's scale tool where everybody portion in the model was scaled taking into account relative separations amongst pairs of markers obtained from gait analysis and virtual marker on model and mass properties of every section was scaled relatively such that the aggregate mass of the subject was recreated. Notwithstanding scaling the measurements of the non-specific musculoskeletal model, the Scale Tool endeavours to change the model's virtual markers by explaining a weighted least squares i.e.WLS issue to locate an arrangement of joint edges that minimize the position error between the model markers and the comparing trial markers. Both scaling and virtual model marker alteration were significant steps in the generation of motion simulation. Model marker conformity through opensim's graphical client interface (GUI) was performed in an iterative way by which the model was seen in a static posture, preceding changing model markers. It is manual adjustment of the weighting variables on inadequately followed model markers that are incorporated into the WLS issue, or variety of the x-, y-and z-directions of virtual markers physically to have them coordinate their comparing trial areas. Muscle fibre lengths and tendon slack lengths of the muscle-tendon actuators were scaled so that they each continue as before rate of aggregate actuator length.

In step 2, joint angles and translation which are summed up coordinate values was illuminated using inverse kinematics tool. These values best imitate the crude marker information acquired during movement catch at gait lab. There is difference between the location of virtual marker in model (subject to joint constrains) and location of markers which were measured at gait lab. The difference is minimized in inverse kinematics using least square issue. In the event that the exploratory kinematics incorporates an arrangement of joint focuses or joint edges created by movement catch programming, these may likewise be incorporated into the plan. Hence, for every casing minimization of the weighted squared error is done using inverse kinematics tool in the test kinematics.

$$\textit{Squared error} = \sum_{i=1}^{markers} w_i({}^{subject}x_i - {}^{model}x_i)^2 + \sum_{j=1}^{joint\ angles} w_j({}^{subject}\theta_j - {}^{model}\theta_j)^2$$

Where joint angles and markers which are required to be weighted separately depends on factors w_i and w_j. The ith joint center and marker 3D location of model and subject were described as ${}^{subject}x_i$ and ${}^{model}x_i$. The jth joint angle estimations of the model and subject are ${}^{subject}\theta_j$ and ${}^{model}\theta_j$.

In step 3, After that, static optimization was utilized to further determines the net joint minutes into individual muscle powers at every moment in time. In the static optimization Tool in opensim utilizes the known movement of the model to illuminate the conditions of movement for the obscure summed up powers (e.g., joint torques) subject to muscle actuation to-power conditions.

In step 4, joint reaction forces for every patient is calculated using joint Reaction Analysis tool in opensim. In between two successive bodies the joint moment and forces acting are evaluated in the model. Every joint structure carries internal load and these joint moments and loads represents those internal loads.

For example, in case of knee joint

$$\vec{R}_{knee} = [M]_{tibia}\,\vec{a}_{tibia} - (\vec{R}_{ankle} + \Sigma\,\vec{F}_{muscles} + \vec{F}_{gravity})$$

Where $\vec{R}_{knee}$ is force acting on tibia from the femur, matrix $[M]_{tibia}$ represents tibial inertial properties. $\vec{a}_{tibia}$ represents tibial linear and angular acceleration in 6 dimensions. $\vec{R}_{ankle}$ is force acting on tibia from the foot. $\Sigma\vec{F}_{muscles}$ represent sum of all muscle forces acting on tibia and $\vec{F}_{gravity}$ represents forces acting on tibia due to gravity.

Similarly, joint reaction forces for hip and ankle joint are estimated.

Chaptor 4. Results

The similarities and differences in joint angles, ground reaction forces, joint reaction forces and indivdual muscle forces of three cerebral palsy subjects from normal subject are reported in this section. Note that, all the joint angles, joint reation forces and individual muscle forces are coming from the simulation of model which is tracking gait anlysis data of respected subject.

Subjects

CEREBRAL PALSY SUBJECTS	SHORT NAME USED
Left leg of subject 1	Sub 1 l
Right leg of subject 1	Sub 1 r
Left leg of subject 2	Sub 2 l
Right leg of subject 2	Sub 2 r
Left leg of subject 4	Sub 4 l
Right leg of subject 4	Sub 4 r

Right leg of normal subject is represented as 'normal'.

4.1. Joint angles

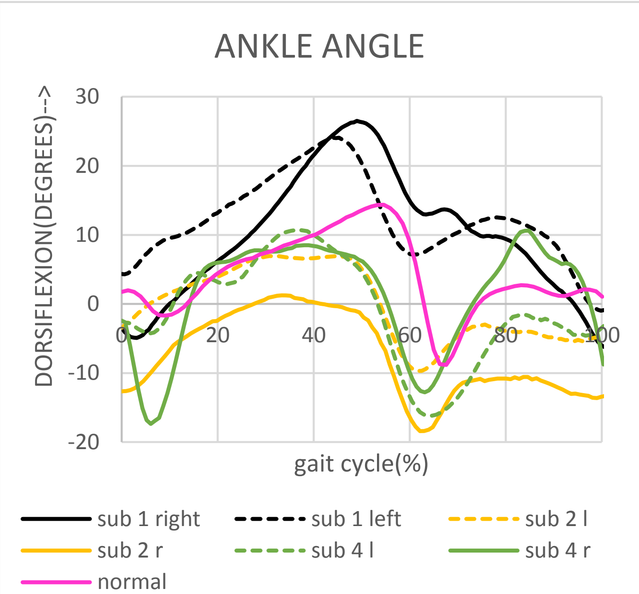

Figure 4.1, Ankle angle

The figure 4.1 is showing ankle joint angles achieved by both limbs of all subjects duiring gait cycle. The subject 1 is showing similar patten of incresing ankle dorsiflexion upto 50% of gait cycle if we compare it with normal subject. However, ankle dorsiflexion is abnormally high through out gait cycle in both legs than normal in subject 1. The peak ankle dorsiflexion in subject 1 reaches to 23° in left leg and 25° in right leg. Whereas, in normal subject it is 15°. Subject 2 and 4 have similarity, there is no linear dorsiflexion from 20 to 50% of gait cycle as seen in normal. The right ankle of subject 2 have more planterflexion throughout gaitcycle.

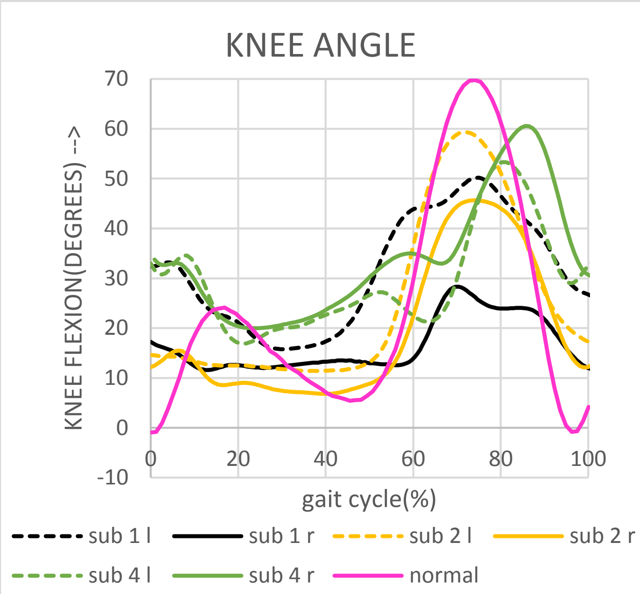

Figure 4.2. knee angle

The figure 4.2 is showing knee joint angle for all subjects which are achieved during gait cycle of respected limb. The similarity which could be seen in all cerebral palsy patient is that knee extension in swing phase starts late.

The first difference which comes into attention is that not in all limbs extension of knee joint happens from 5 to 45 % of gait cycle. The both legs of subject 2 and right leg of subject 1 have no extension in knee from 0 to 45%. The next difference is, subject 4 starts and ends his gait with more flexed knee. Also, overall subject 4 is showing high knee flexion. Another difference observed, Right knee of subject 1 have very less flexion in the swing and it seems subject 1 have stiff knee in both limbs.

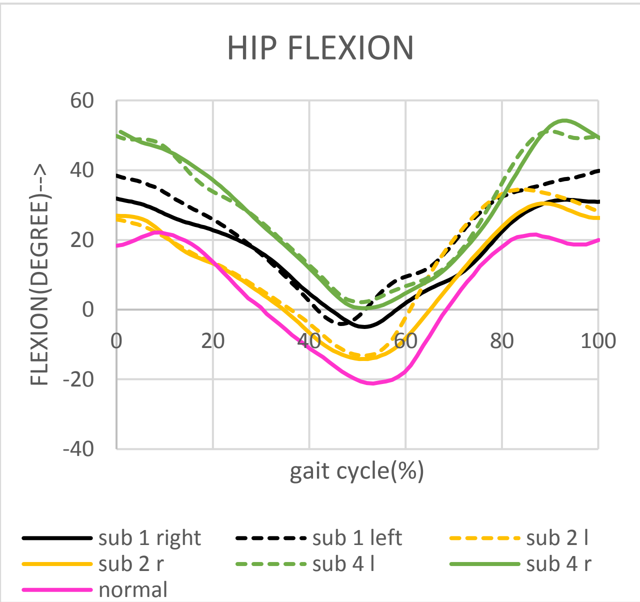

Figure 4.3, Hip flexion

The figure 4.3 shows hip flexion of respected limbs for all subjects during gait cycle.

Hip flexion starts after 50 % of gait cycle in all legs of respected subjects but in left leg of subject 1 it starts early.

It is seen that subject 2 have more extended hip throughout stance phase and also in late swing phase. Whereas, subject 4 shows more flexed hip throughout stance phase.

4.2. Ground reaction forces

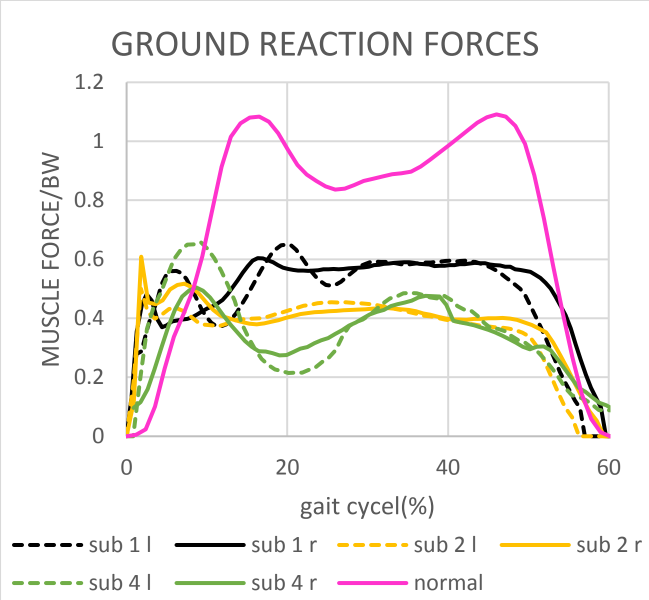

Figure 4.4, Ground reaction forces

The figure 4.4 shows ground reaction forces for all subjects. The ground reaction forces in all cerebral palsy subjects are very low i.e. below 60% of body weight. The anticipated reason for low ground reaction forces is acquisition error caused during gait analysis.

The subject 1 and subject 2 are not showing any depression in ground reaction forces during mid stance which actually happens in normal subject. The maximal weight acceptance occurs early in all cerebral subjects. The maximal weight acceptance causes first peak.

4.3. Joint reaction forces

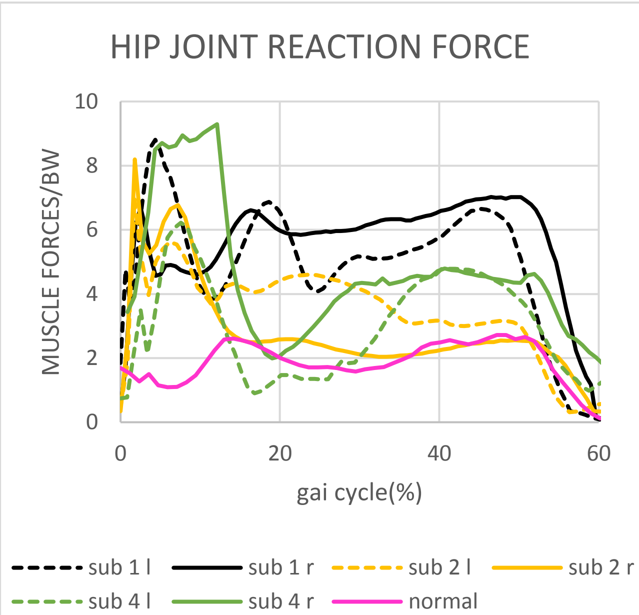

Figure 4.5, Hip joint Reaction

The figure 4.5 shows hip joint reaction forces for all subjects. It is very clear that cerebral palsy subjects mostly have high hip joint reaction forces than normal.

There is sudden rise in hip joint reaction forces in cerebral palsy subjects after heel strike. Whereas in normal subjects there is no increment till 10 % of gait cycle.

The pattern of hip joint reaction forces is different in all cerebral palsy subjects. The subject 1 and 2 have no rise in hip joint force in late stance which actually happen in normal and sub 4.

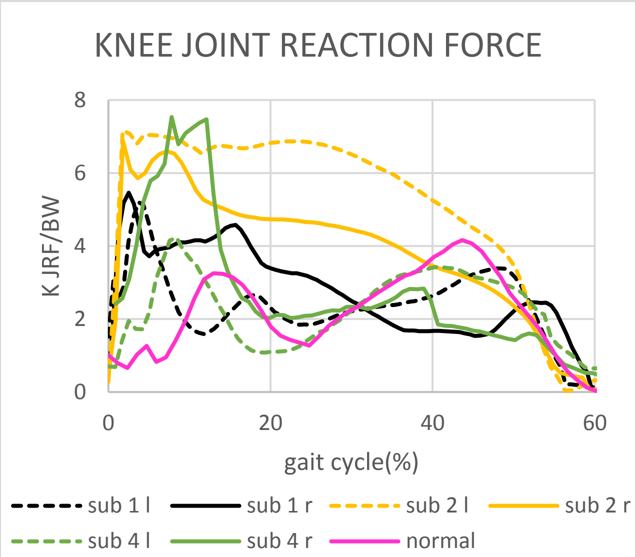

Figure 4.6, Knee joint reaction forces

The figure 4.6 shows knee joint reaction forces for all subjects. Knee joint reaction forces in cerebral palsy subjects also rises immediately after heel strike. The knee joint reaction forces are highest in subject 2 and continually decreases with no rise in late stance. The knee joint reaction forces in subject 1 are low than subject 2 and also they have a small increment in late stance. Knee joint reaction forces during late stance in subject 1 and subject 4 are lower than normal subject. Initially, the right leg of subject 4 is showing very high knee joint reaction force and falls very quickly to normal range with no rise in late stance.

4.4. Muscle forces

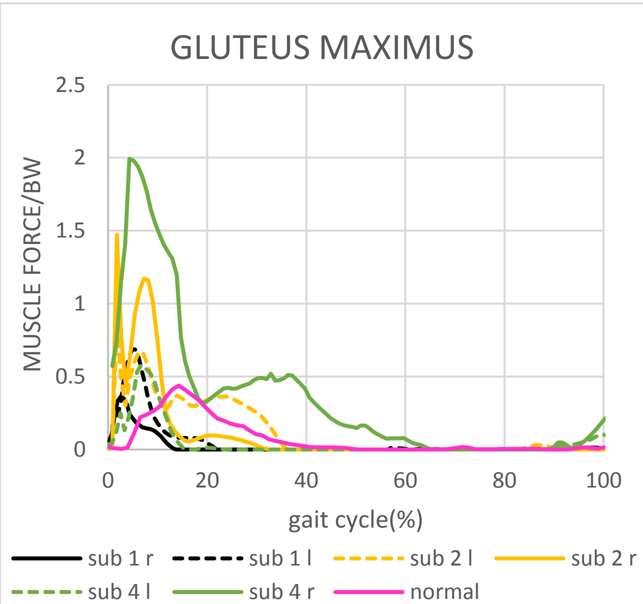

Figure 4.7, Gluteus Maximus

The figure 4.7 shows force produced by gluteus maximus muscle in all subjects. Gluteus maximus muscle is generating higher force in all cerebral palsy subjects than normal. Also, in cerebral palsy subjects the force is generated much earlier than normal.

The much higher forces are observed in right leg of subject 2 and 4 than others.

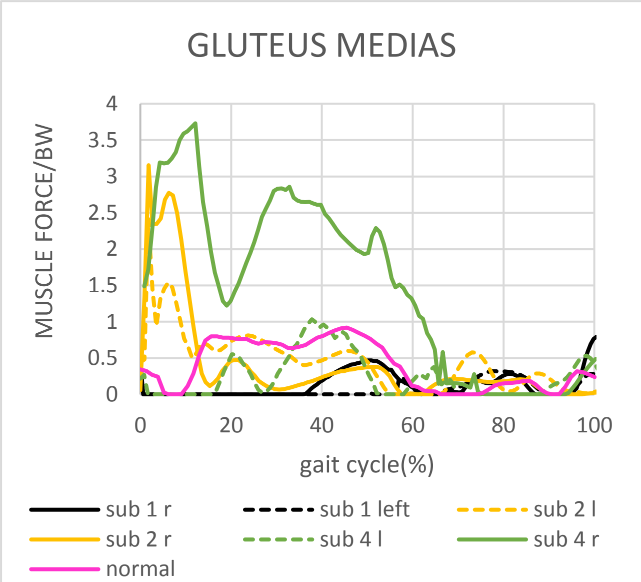

Figure 4.8, Gluteus Medias

The figure 4.8 shows force produced by gluteus medias muscle in all subjects. Gluteus medias muscle is not producing force in both legs of some subjects. First example is subject 1, the muscle is only generating force in right leg and the magnitude of force is very less as compare to normal. The time period for which muscle generated force is very small in stance phase. The muscle is active in late stance. whereas in normal subject the muscle is used from the start of mid stance to late stance. In the subject 4, the right leg gluteus medias is producing very high force but the left leg muscle is staying weaker in comparison to normal. In subject 2, sudden rise is seen production of force by gluteus medias after heel strike and it falls below normal at 15% of gait cycle.

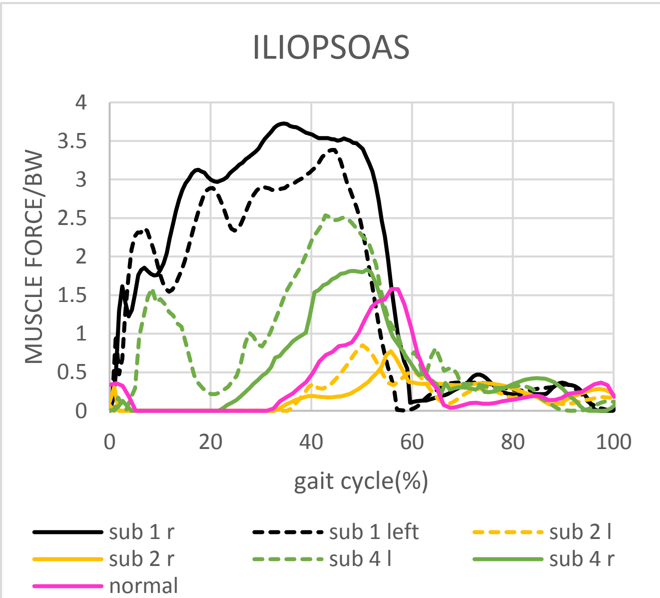

Figure 4.9, Iliopsoas

The figure 4.9 shows force produced iliopsoas muscle in both legs of all subjects. In the subject 1 the magnitude of force produced by iliopsoas muscle is highest followed by subject 4. Subject 1 and 4 both are producing higher force than normal. Iliopsoas muscle in subject 2 is producing is much less force than normal.

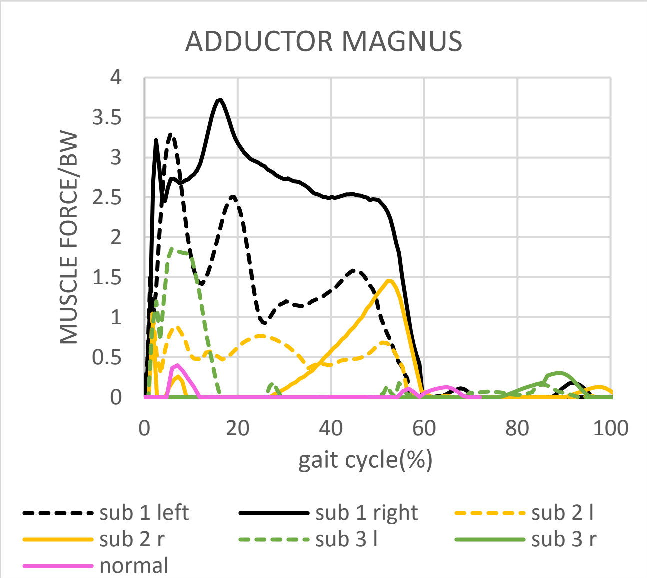

Figure 4.10, Adductor Magnus

The figure 4.10 shows force produced by adductor magnus muscle in both legs of all subjects. The magnitude of force produced by adductor magnus in normal subject is very small. On the other hand, in the subject 1 the adductor magnus is producing enormous amount of force. The subject 2 is also using adductor magnus muscle well.

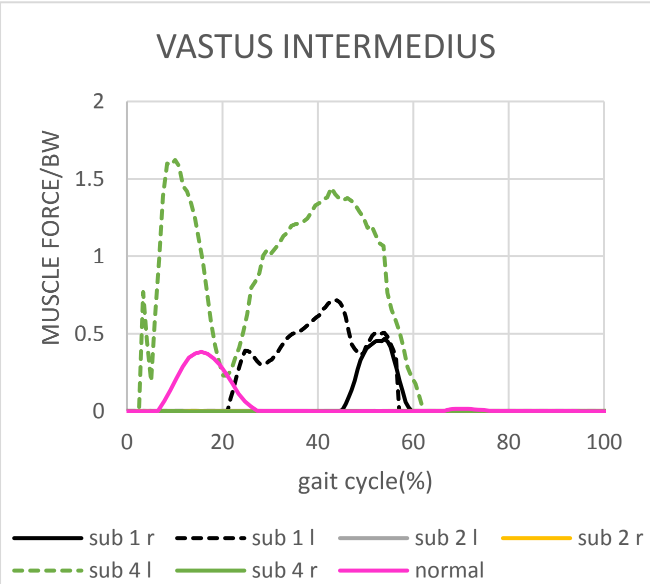

Figure 4.11, Vastus Intermedius

The figure 4.11 shows force produced by vastus intermedius muscle in both legs of all subject. It is seen that in both legs of subject 2 and in right leg of subject 4 negligible amount of force is produced by vastus intermedius. Subject 1 is using vastus intermedius in late stance. Whereas in normal subject vastus produced force in early stance. Vastus intermedius is used strongly two time in left leg of subject 4

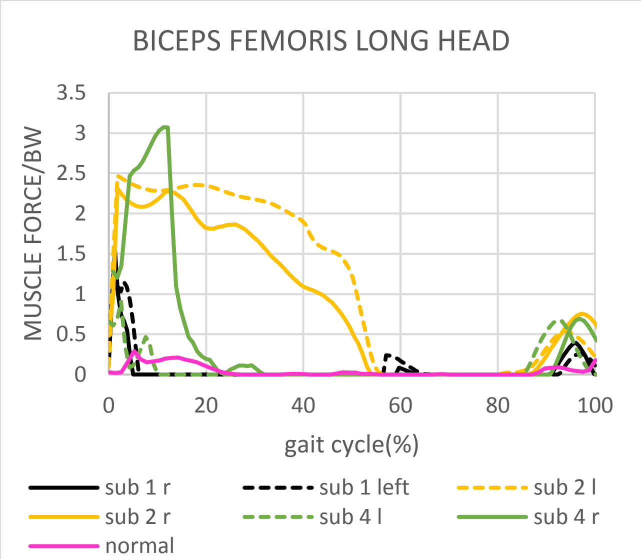

Figure 4.12, Biceps Femoris Long Head

The Figure 4.12 shows force produced by biceps femoris long head in both legs of all subject. The biceps femoris is strongly acting in subject 2 throughout the stance phase.In the right leg subject 4 it producing high force in early stance. In most subjects this muscle is producing force from late swing to early stance.

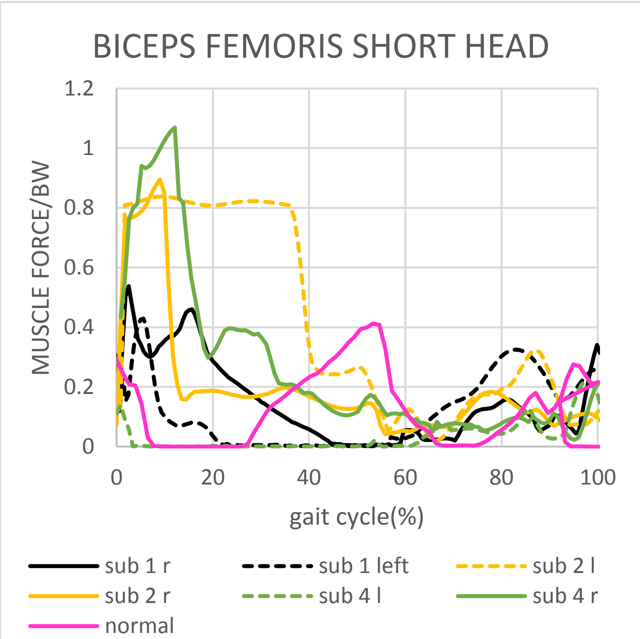

Figure 4.13, Biceps Femoris Short Head

The figure 4.13 shows force produced by biceps femoris short head muscle in all subject. It is very clear the that this muscle is also producing high force in most of the cerebral palsy subjects than normal. This muscle is strongly used in early stance phase and in swing phase in cerebral palsy subjects. Only in the left leg of subject 4 it is producing less force.

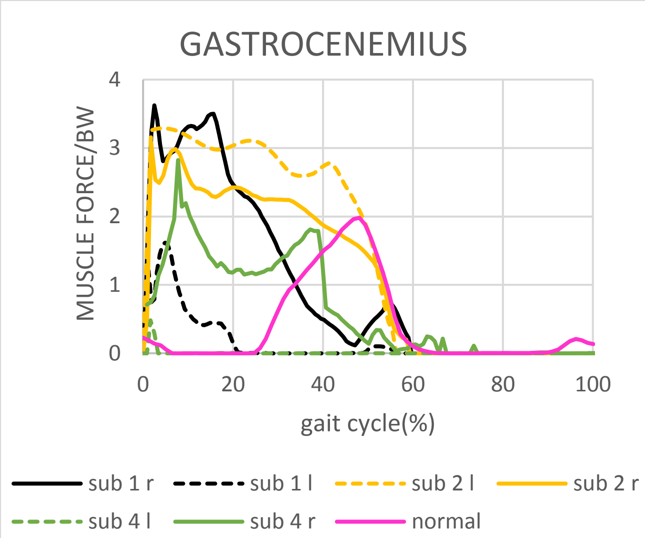

Figure 4.14,Gastrocenemius

The figure 4.14 shows the forces produced by gastrocnemius muscle in all subjects. This muscle is producing high force in some cerebral palsy subjects in early stance phase and shows reduction trend after that. Whereas, in normal subject it is not active in early stance phase but produces approximately same amount force as CP during late stance. In both legs of subject 2 the gastrocnemius is used strongly. Also in the right leg of subject 1 it is used strongly.

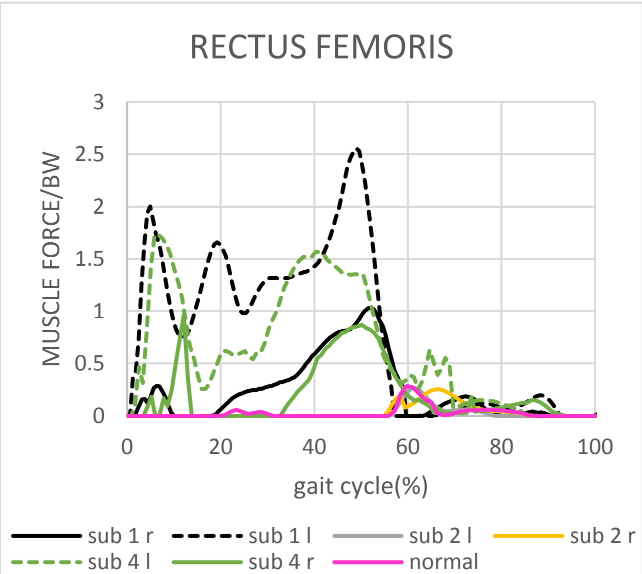

Figure 4.15, Rectus Femoris

The figure 4.15 shows the force produce by rectus femoris muscle in all subjects. The rectus femoris muscle is very strongly used subject 1 and subject 4 as compare to normal subject. The use of rectus femoris by subject 2 is negligible.

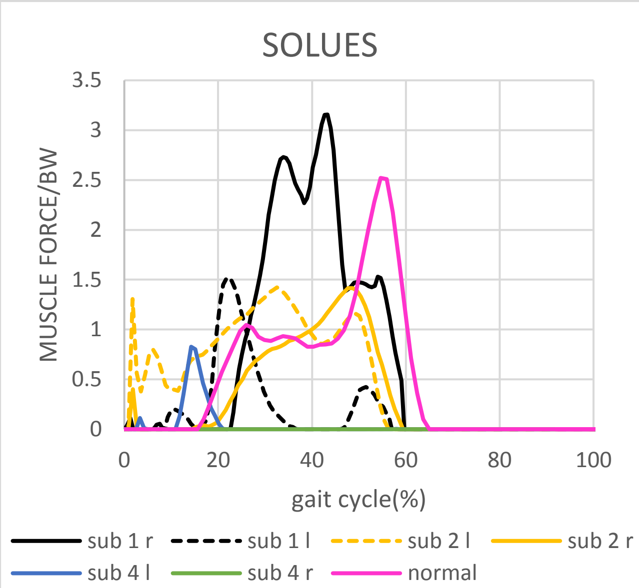

Figure 4.16, Soleus

The figure 4.16 shows the force produced by soleus muscle in all subjects. It is seen the subject 1 and 2 are using this muscle but not sub 4. In the normal subject it produces maximum force during late stance but in cerebral palsy subject maximum force production is happening earlier than normal.

Chapter 5. Discussion

Discussion on results subject wise is done in this section. The results obtained are compared with other studies in literature. The anticipated reasons for variation in joint and muscle forces are explained in this section.

5.1. Subject 1

Hip joint reaction forces are near about six time the body weight in subject 1. This is almost double than normal subject. The anticipated reason for this is high muscle forces acting on hip joint. On both legs, muscles acting on hip joint which are producing higher forces than normal subject are iliopsoas, Adductor Magnus. After carefully analysing the trial on opensim it is observed that the subject 1 is using iliopsoas muscle powerfully in stance phase to flex the hip in swing phase. It is happening because of stiff knee or insufficient knee flexion during swing phase. The subject 1 is unable to get foot clearance in swing phase due to stiff knee and therefore he has to drag his foot and leg using iliopsoas muscle. The effect of high force generated by iliopsoas muscle could be seen in pelvic tilt movement in subject 1. The subject 1 is showing high pelvic tilt as compare to normal. It is also observed that left knee is showing some extension from 15 to 45 % of gait cycle but not right and the one of the anticipated reason for that is high activity of rectus femoris muscle in left leg. One more muscle which is effecting knee angle is gastrocnemius muscle. It is not active in left leg but active in right. The effect of gastrocnemius activity on knee during early stance is discussed in detail in the following part of discussion section. Also, the vasti muscles in left leg gets active early and stay active for longer period. Vasti muscle is generating knee extension moment from 50 to 70 % of gait cycle. But in right leg vasti muscle is acting late and for less time and it generate knee extension movement from 70 to 90 % of gait cycle. Note that, force produced by rectus femoris also contributes to hip joint reaction force. On the other hand, adductor Magnus is powerfully used to get clearance for the contralateral limb. Subject 1 is producing more hip abduction movement in order to get clearance in swing phase for contralateral limb. To stop or to put limit on this abduction movement subject 1 is using adductor Magnus very powerfully during stance phase. It is to be noted that subject 1 is shifting centre of mass of body to one side to produce abduction movement. Hence, adductor magnus have to support the whole body to stop abduction at hip and shift the centre of mass of body to other side.

The gluteus maximus muscle in subject 1 gets active earlier than in normal subject. This happens because subject 1 starts putting weight of body on leg immediately after heel strike i.e. loading response (gait cycle) starts early. This can be observed from the graphs of ground reaction forces. The subject 1 ground reaction force graph show sudden rise with heel strike as compare to normal. To stop the flexion of hip happening due to the ground reaction forces and upper body weight acting on hip, the extension moment is produced by hip extensor gluteus maximus immediately. It is also seen that left leg gluteus maximus is producing more force. This may be happening because of more flexed knee at left side. With more flexed knee during loading response the gluteus maximus have to produce more force to support upper body as the centre of mass of upper body shifts backward and less body weight support is provided by the skeletal. The gluteus medias muscle which is used to stop the pelvic drop to opposite side during stance phase is used very less in subject 1. It can be seen that in subject 1 the activity of gluteus medias is very less and the effect of this is observed in simulation i.e. the subject 1 has continued pelvic drop to opposite side during stance phase. Where as in normal subject pelvic drop to opposite side is stopped and reversed (by two degrees) with help of gluteus medias muscle during midstance. Note that range of pelvic movement in normal subject is 7^{o}. Whereas, in subject 1 it is 10^{o}. Knee joint reaction forces are also high in subject 1 than normal subject during the early stance. Main muscle which could be consider responsible for the high knee joint force in right leg is gastrocnemius. The gastrocnemius muscle is witnessed producing high muscle forces in early stance, in a very similar pattern as observed in knee joint reaction force. The gastrocnemius which can work as knee flexor could also be consider responsible for no or very less knee extension from 15 % to 45 % of gait cycle in right leg which actually happens in normal subject. This can be proved by comparing the left and right leg. In left leg the gastrocnemius is producing less force than right leg and there is knee extension from 15 to 45 % of gait cycle in left leg. Note that, gastrocnemius is bilateral articular muscle it also spans ankle joint but subject 1 had calf recession. In calf recession gastrocnemius muscle is released from Achilles tendon and hence function of gastrocnemius to do plater flexion ankle is terminated. Therefore, it is acceptable even with high activity of gastrocnemius muscle there is no abnormal planter flexion happening at ankle which actually happens in patient with equines gait. Another muscle which could be consider responsible for less knee extension from 15 to 45 % of gait cycle is the biceps femoris short head which spans knee joint and work as knee flexor. It is producing force for longer period in right leg of subject 1 i.e. from 0% to 40% of gait cycle. For the right leg in addition to ground reaction forces the main muscle contributing to knee joint reaction forces is rectus femoris. The pattern of forces observed in rectus femoris is similar to knee joint forces. The soleus muscle in right leg of subject 1 is producing high force. Soleus muscle spans ankle joint only. The function of soleus muscle is it to do plantarflexion at ankle joint.

The variation in angle of ankle joint affects the force required by soleus to perform its function. It can be seen that subject 1 have high ankle dorsiflexion throughout the stance phase. Due to this high ankle dorsiflexion the moment arm of soleus muscles gets small and the force required to perform ankle plantarflexion increases. The small moment arm is one factor contributing to high soleus muscle force in subject 1. After careful observation of simulation, it is found that the subject 1 is trying/struggling to balance body on right leg even the time taken to complete stance phase of right limb is more. As the soleus muscle is used to stop the forward fall of body by pushing the fore foot downward. So, during stance subject 1 may be using soleus muscle as it is used to maintain the standing posture if the body is falling forward forcefully.

5.2. Subject 2

Hip joint reaction forces in subject 2 also rise suddenly with heel strike. The reason is same subject 2 start putting load on leg immediately after heel strike. The main muscles which are contributing to hip joint force are gluteus medias, gluteus maximus and biceps femoris long head. Gluteus medias muscle is well used by subject 2 to stop the pelvic drop to opposite side. The gluteus medias are acting immediately in supporting body weight and also absorbing the sudden initial shock. also, overall there is less pelvic drop in subject 2. This patient is showing more extension and less flexion of hip and one of the anticipated reason for that is high force produced by hamstring muscles. This is proved in simulation, two hamstring muscles used in model i.e. biceps femoris long and shot head are observed generating high force. The patient also had hamstring transfer surgery and hamstring transfer surgery is only done if patient have abnormal high activity of hamstring muscle. In hamstring transfer, the function of muscle to produce knee flexion is lessened by transferring semitendinosus tendon from tibia to femur. But, hamstring muscles can perform extension at hip with same capacity even after transfer surgery. The other part of hamstring muscle which is still attached to tibia can perform flexion of knee required for the foot clearance in swing phase. In subject 2, it is observed because of the high activity of hamstring muscles the patient is getting better flexion of knee in swing phase specifically in left leg. Note that, biceps femoris short/long head are part of hamstring muscles. There origin, insertion and function is discussed in literature review section refer there.

In subject 2, Gluteus maximas muscle is used very powerfully immediately after heel strike to extend hip and in combination with soleus muscle it is extending knee as well. Also, Because of activity of soleus muscle Subject 2 is moving with more ankle plantarflexion. The less flexed hip during start of stance phase due to hamstring muscles and combination of soleus and gluteus maximus forces are responsible for extension at knee. So, that's is why vasti muscle is not producing any force to extend knee. Note that, patient had rectus femoris transfer surgery and in rectus femoris transfer surgery the function of rectus femoris is changed from knee extensor to knee flexor. The rectus femoris can be seen contributing during initial swing phase in simulation. Putting in nutshell, Soleus and gluteus maximus are replacing the function of vasti and rectus femoris along with help hamstring at knee. Gastrocnemius muscle in this patient again producing high force in both leg and this subject also had calf recession. Due to calf recession, the gastrocnemius muscle can only perform flexion at knee. The effect of high force produced by gastrocnemius muscle during stance phase could be seen as there is no or very less extension of knee from 10 to 45 % of gait cycle in both legs. Gastrocnemius muscle is responsible for no or very less knee extension. This fact can be proved by comparing the different subject. In the subject 4, the gastrocnemius is producing very less force and there is extension of knee from 5 to 20. In the left leg of subject 1, the gastrocnemius muscle is producing less force there is knee extension happening in same leg from 5 to 30% of gait cycle. Rest all have high gastrocnemius muscle force and there is no or negligible knee extension in them.

5.3. Subject 4

In subject 4, the first maximum observed in Hip joint reaction forces is occurring during weight acceptance and second maxima in hip joint reaction forces is occurring when body is pushed forward. The hip joint reaction forces at left leg are very less than right. The anticipated reason for this, as the subject 4 is not putting load on left leg and the body centre of mass remains shifted towards right. There is huge pelvic drop to right side. This is happening because of weak abductor muscle on left side i.e. gluteus medias. Whereas, the gluteus medias is generating high force in right leg. Extremely high force in right leg of gluteus medias may be generated in patient as he has scissor gait. In Scissor gait patient walks with more hip adduction and because of higher hip adduction the moment arm of gluteus medias decreases. Therefore, higher force is required to produce moment at hip.

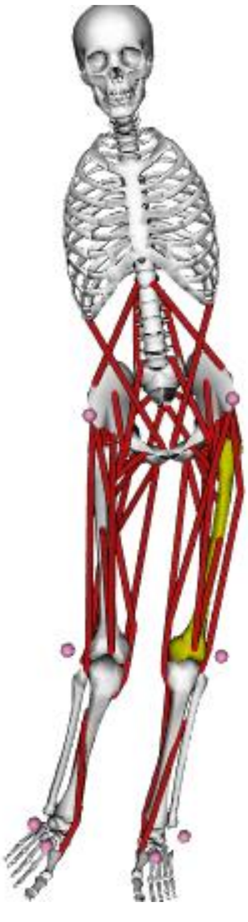

Figure 5.17

The upper body of subject 4 is listed towards right during gait cycle of left limb (figure 5.17).

The force produced by right gluteus maximus is 2x than body weight and is considered as extremely high. The reason for this is high flexion angle of hip during heel strike. This subject 3 have hip flexion of 50^{o} during heel strike. To support the whole body or to push body centre of mass vertically upwards, the gluteus maximus have to extend the hip with great power. Therefore, higher force is required to produce moment at hip. Biceps femoris is producing high force in subject 4 right limbs and the effect of biceps femoris could be seen on knee i.e. the maximum knee flexion angle during swing phase is more in right limb. In left leg the iliopsoas muscle activity is high and the reason for this can be found from the fact that patient is not using left leg confidently therefore he is trying and forcefully pushing leg forward by generating hip flexion through iliopsoas. The rectus femoris and vasti muscle are producing good amount of force two time in stance phase. The outcome of this is two-time knee extension occurring from 5 to 20 % and from 50 to 60 %.

Discussion summary

There is huge literature on estimation of muscle and joint forces during unimpaired gait. However, there are no direct studies on estimation of muscle and joint forces in children having abnormal gait due to cerebral palsy. But, there are some studies which are about contribution of muscle in mass centre accelerations and joint angular accelerations in crouch gait. There are studies in which musculoskeletal modelling and simulation is used to find out muscle contribution in hip and knee joint extension during stance phase. There are studies on tibiofemoral force during crouch gait and tibiofemoral force during variations in muscle activity. After comparing the results of simulation of this project with finding of these studies it is discovered that the model gives good idea about the muscle involved in abnormal gait pattern of cerebral palsy subjects. The result obtained from the model was representative of cerebral palsy child gait as explained below.

As all three cerebral palsy subjects have different gait patterns, therefore the muscle activation patterns are different as well. Depending on the walking kinematics of subjects, different muscles gets active and produce force to balance the equation of motion. The average muscle forces are higher in cerebral palsy subjects in comparison to normal subject. This Fact is previously reported in the study (Steele et al. 2010). Iliopsoas muscle is used very strongly in subject 1 ; subject 4 during stance phase to drag foot in swing phase. The adductor magnus muscle is producing high force in subject 1 as compare to normal and the reason for that is high abduction movement. The gluteus maximus muscle in all cerebral palsy subjects starts producing force immediately after heel strike. This happen because the loading response phase starts early. Gluteus maximus works against the hip flexion happening due to ground reaction forces and body weight acting across joint and this is also reported in (Arnold et al. 2005). One another reason of immediate surge in gluteus maximus muscle force after heel strike is, no flexion of knee after heel strike which actually happens in unimpaired gait to absorb the shock which is produced after foot strike on ground and leg start accepting weight of body. The gluteus medias muscle is inactive in subject 1 and which causes of pelvic drop to opposite side. The gastrocnemius muscle is highly active in left leg of subject 1 as well as in both legs of subject 4 and the effect of gastrocnemius is seen on knee. Gastrocnemius muscle have knee flexion moment. Its effect on knee is also reported in (Steele et al. 2010). The subject 1 had calf recession that is why there is no ankle plantarflexion happening even with high activity of gastrocnemius. Higher activity of biceps femoris muscle is causing more extended hip in subject 2. This could be compare with result reported in (Jonkers et al. 2003).

High force production by soleus and gastrocnemius in subject 2 is causing more than normal plantarflexion at ankle throughout the gait cycle and this could be compared with the function of gastrocnemius and soleus as reported in (Neptune et al. 2004).
In subject 2, Knee extension is happening due to the force couple made by gluteus maximus and calf muscle . Both of these muscle do not cross knee joint and the muscle which is primarily responsible for knee extension i.e. quadriceps femoris is not producing force in subject 2. In subject 4, the hip joint reaction forces are very less at left leg. This is so, as subject 4 is moving with body centre of mass shifted to right side and with pelvic drop to right side. The left abductor muscle i.e. gluteus medias is seen very weak in simulation. The right gluteus maximus is producing high force to extend hip and this is happening because of high flexion angle of hip during heel strike. Subject 4 have weight of 81.9 kg and have high hip flexion during heel strike in addition to more flexed knee. Therefore gluteus maximus muscle of subject 4 have to produce high force to extend the hip against the body weight and ground reaction forces acting on hip. This is well represented in simulation. The knee joint forces produced in the cerebral palsy subjects could be compared with results reported in (Demers et al. 2014),(Steele et al. 2012). The muscles which effect knee joint forces are well described by the model used in this project.

Overall Summary

More research is required as to know how individual muscles affect movement in an abnormal gait. It is hard to design a treatment strategy which will target muscles most likely to enhance dynamics of gait. The objective of this project was to estimate the muscle and joint forces in cerebral palsy patient and find the relation between abnormal gait pattern and forces generated by muscle. The generic musculoskeletal model available with opensim is used. It was tried to find weather this model can be used for child effected with cerebral palsy to get reliable results. There were no major modification done in model. Only it was scaled down on the basis of height and weight of patient. I choose this project because I came to know that about 2 to 2.5 children out of 1000 born suffers with cerebral palsy. The advancement of medical technologies give rise to the survival of premature and smaller babies and due to this rate of children born with cerebral palsy is constant. I found musculoskeletal system modelling and simulation has big potential to improve rehabilitation process of child who have gait effected from cerebral palsy. It will be better to work on this and improve skills considering its future prospect. The thesis have six chapters i.e. introduction, literature review, method, results, discussion. The first chapter introduces to the topic and objective of research project. The second chapter is literature review. The relevant literature to this project i.e. cerebral palsy, human gait, biomechanics of musculoskeletal structure, important lower limb muscles used in gait, phasic activity of muscle in gait and musculoskeletal modelling and simulation is discussed. This literature review is foundation study on human movement science. It provides knowledge to interpret the results of musculoskeletal modelling and simulation. The third chapter describes the method used in this research project to estimate muscle and joint forces. This chapter describes how 3d gait analysis data is used in musculoskeletal modelling and simulation. The fourth chapter contains the result of simulation. It contains joint kinematics, individual muscle forces, joint reaction forces for all three cerebral palsy subjects and one normal. The fifth chapter is discussion and in this chapter the results are discussed. The anticipated reasons of variation in joint and muscle forces are explained in this section from the knowledge acquired with literature. The finding of this project are explained as follows. It is found in results that musculoskeletal model and method used in research project could be used to get important information i.e. muscle and joint forces in child with cerebral palsy. The model well describes which muscle have to produce more force to overcome the more flexed knee and hip joint. The model also defines the overly active muscle like rectus femoris which causes stiff knee gait during swing phase. It also described that muscles like calf muscle when they are over active they make couple with another muscle like Gluteus maximus to extend knee joint. Because of them muscles like quadriceps which are main muscle responsible knee extension is found producing no force. The model also well describes that overly active gastrocnemius muscle can affect the knee joint with and without calf recession. All these finding are in agreement with previous studies found in literature. The Model described the strong use of iliopsoas muscle to flex leg in swing phase when subject is dragging foot on ground. The use of adductor magnus muscle to stop abduction movement. Overall, model can be used as predictive tool to understand how cerebral palsy subjects uses alternative strategy to complete their gait.

Conclusion

This study identified muscles that significantly affect the gait pattern in children having abnormal gait due to cerebral palsy. This study further revealed that children affected by cerebral palsy are producing high muscle force during gait than healthy person. The hip and knee joint forces are substantially affected by the muscles crossing them. In fact, Muscle which cross only hip or ankle joint are used more to produce moment at knee in children affected with cerebral palsy therefore they are also responsible for knee joint forces. It is also concluded that children affected by cerebral palsy are walking with increased muscle and joint forces due to reasons like excessive flexion of knee during stance phase. Increased muscle and joint forces could contribute to cartilage degeneration and joint pain. The previous researches on 'muscle contribution in abnormal gait due to cerebral palsy' also gives similar finding. Justification of results coming out of simulation is also done by considering the anatomic game plan of muscle in respect to the skeletal structure in actual human body. Considering everything it is revealed that model used in this project could be used to get general idea about the muscle responsible for abnormal gait pattern in cerebral palsy child.

Limitation and future work

It is seen that, in simulation abnormally high joint angles are producing false forces in some muscles. Also, Generic parametrized model used in simulation was scaled according to anthropometry of respected subject. The generic model scaled to smaller anthropometry in combination with high joint angles can cause smaller moment arm of muscle. Due to smaller moment arm, the muscle has to generate high force to balance equation of motion.

Abnormally High muscle forces were generated in some muscle during simulation in subject 1. Tibialis posterior muscle is generating abnormally high force in subject 1 in both legs. The moment arm of this muscle gets very small due to high ankle dorsiflexion happening in subject 1. Therefore, the default model which comes with opensim is not fully compatible to be used with every cerebral palsy subject and it have some limits in the form of joint angles. These limits can be effected when model is scaled. Model requires improvements and modification which could be done in future.

For further validation of results, the reliance on kinematics and ground response should have to be lessen by making use of forward dynamic optimisation which also enables to learn more, i.e. power, length, speed, actuation connections of the muscles, and with recorded electromyography signals during walking.

<u>Low Ground Reaction Forces</u>

Low ground reaction forces does not have critical effect on finding of this project because the pattern and timing of ground reaction forces is right. As long as pattern and timing is precise, the ground reaction forces will act on the foot of subject at right time i.e. when the actual contact of foot occurred with ground during gait analysis trail at lab. Therefore, only the difference will be in the magnitude of muscle and joint forces and that to will be very less in case of cerebral palsy subjects because of following reason. The magnitude of muscle and joint forces not only depends on ground reaction forces, It also depends on weight of patient, joint angles achieved during gait, kinematics of body segments, Activation of muscles. It is seen in results that magnitude of muscle and joint forces is high in cerebral palsy subjects as compare to normal subject. The average total muscle force generated during stance phase by cerebral palsy subject is 8 ±.4 times body weight versus 5 ±.2 time body weight in unimpaired gait. As the range of magnitude of muscle force is high therefore the difference in ground reaction force which is .4 times the body weight does not have major effect on results.

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Appendices

Supplementary material…

Drop box link- https://www.dropbox.com/sh/6jexj27ezs7d55k/AADxp9_mtf-9wwLd0j266HgVa?dl=0

Link to download opensim software- http://opensim.stanford.edu/

Link to download MotoNMS toolbox- https://simtk.org/projects/motonms/

Important lower limb muscle – Origin, insertion point and function

Gluteus medias

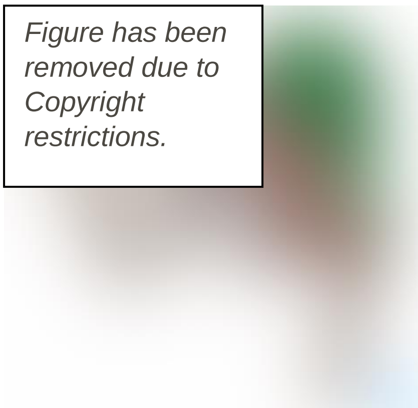


Figure 0.4(Kenhub)

Dorsal gluteal musculature contains the gluteus medias and it forms the middle layer. It is also known as small gluteal muscle. Muscle which is highlighted green is gluteus medias in Figure 0.4.

Figure 0.5(Kenhub)

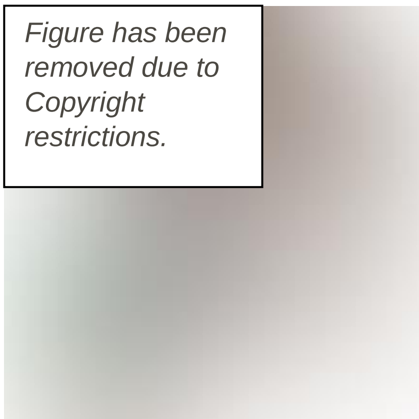


Figure 0.6(Kenhub)

Origin- Between the inferior and anterior gluteal lines of the ilium is the origin of the gluteus medias(Figure 0.5)(Stitik 1997).

Insertion- At lateral surface of the greater trochanter into the strong flattened tendon the fibres of gluteus medias meets (Figure 0.6).

Function- The function of gluteus medias is to stop pelvis drop to the other side during gait. In this way this muscles hold up body on one leg during gait.

Gluteus maximas

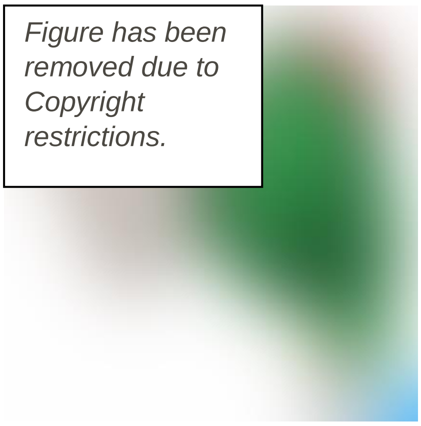


Figure 0.7(Kenhub)

out of three gluteal muscles, the gluteus maximas (Figure 0.7) is the most superficial and largest. At each side of the hips gluteus maximas has big share in the fabrication of the shape and appearance.

Origin- There four different fixed attachments of gluteus maximas(Schellhas 1990): behind the posterior gluteal line of ilium(Figure 0.8), sacrotuberous ligament(Figure 0.9), the thoracolumbar fascia(Figure 0.10) and dorsal part of sacrum (Figure 0.11),

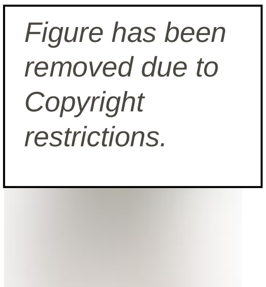


Figure 0.8(Kenhub)

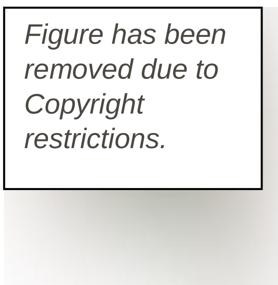


Figure 0.9 (Kenhub)

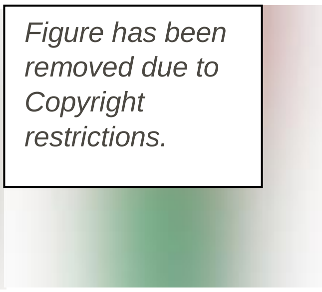


Figure 0.10(Kenhub)

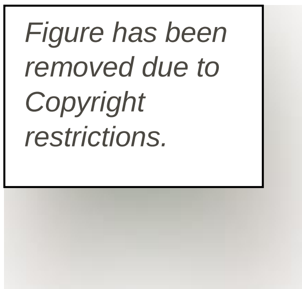


Figure 0.11(Kenhub)

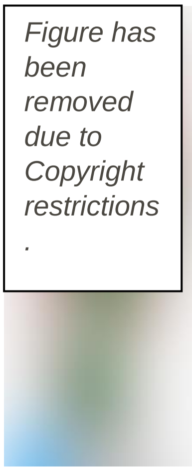
Insertion(Schellhas 1990)- the gluteal tuberosity(femur) is location where gluteus maximas caudal fibres inserts(Figure 0.12). However, at iliotibial tract the opposite cranial fibres inserts (Figure 0.13). Iliotibial tract inserts into the lateral condyle(tibia) and it is a fibrous band which is very strong.

Figure 0.12(Kenhub)

Figure 0.13(Kenhub)

Function- the most powerful extensor of hip is gluteus maximas during gait. It also rotates the hip outward.

Vastus Intermedius



On the front of thigh there is a large muscle group which contains four muscles and the name of that muscle group is quadriceps. Vastus intermedius is one muscle out of four quadriceps have (Figure 0.14). It lies on the front of thigh between vastus medialis and vastus latrialis. It lies behind rectus femoris and visible only after rectus femoris dissection. When knee is flexed fully intermedius cannot stretch more because it is the most middle and deeper muscle in the group of quadriceps muscle. Unlike rectus femoris with extension of hip, the vastus intermedius cannot be stretched more.

Figure 0.14(Kenhub)

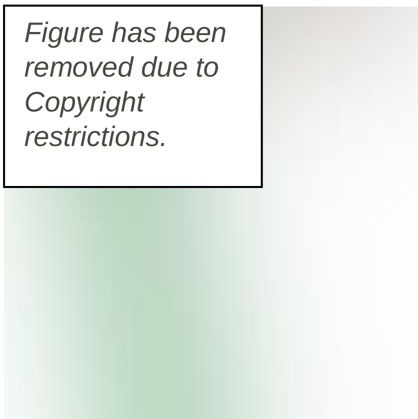


Figure 0.15(Kenhub)

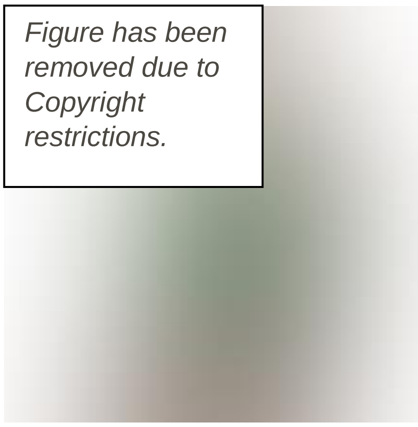


Figure 0.16 (Kenhub)

Origin- vastus intermedius originates from the upper front side of femur(Figure 0.15)(Schellhas 1990).

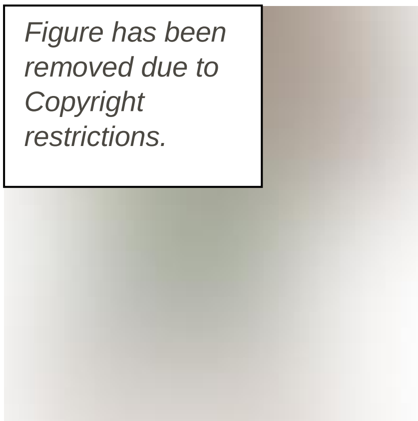
Insertion- vastus intermedius inserts at the common insertion tendon where other muscle of quadriceps group inserts(Figure 0.16)(Schellhas 1990).

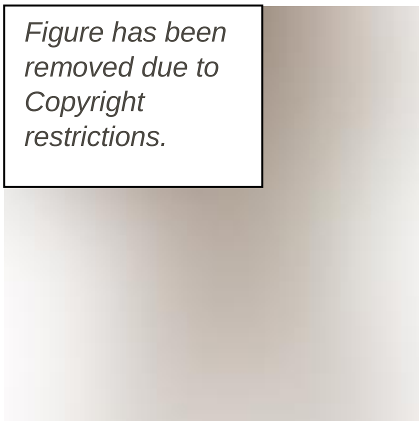
Function- The only extensor of knee is vastus intermedius along with other quadriceps muscles. In all the activities like walking, standing up from the sitting position, stairs climbing which requires knee stretching vastus intermedius plays main role. While, standing bucking of knee is stopped by vastus intermedius.

Rectus femoris

Figure 0.17(Kenhub)

Rectus femoris (see Figure 0.17) is also part of quadriceps muscle. The other 3 muscles of quadriceps are covered by rectus femoris as it lies above them in front of thigh. The middle portion of thigh is occupied by rectus femoris.





origin(Schellhas 1990)- Rectus femoris actually have two fixed attachments one at the acetabulum upper margin(Figure 0.18) and other at the anterior inferior iliac spine(Figure 0.19)

Figure 0.18(Kenhub)

Figure 0.19(Kenhub)

Insertion(Schellhas 1990)- its fibres distally end into same quadriceps insertion tendon as described above in vastus intermedius (Figure 0.16).

Function- At the hip joint, rectus femoris can flex thigh and also it can do knee extension. The flexion capability of rectus femoris decreases when knee was extended. The reason for that is as the muscle shortening is already happened and therefore it lacks active sufficiency. In that situation hip flexion is done by other hip flexor muscles like iliopsoas, tensor-fasciae-latae. Same is the situation when the hip is flexed the capability of rectus femoris to extend knee

Biceps femoris muscle

At the posterior, or back of thigh is location biceps femoris muscle. According to its name it has two parts known as short head and long head. Biceps femoris long head (Figure 0.20) is considered as part of group of muscle known as hamstrings.

Figure 0.20(Kenhub)

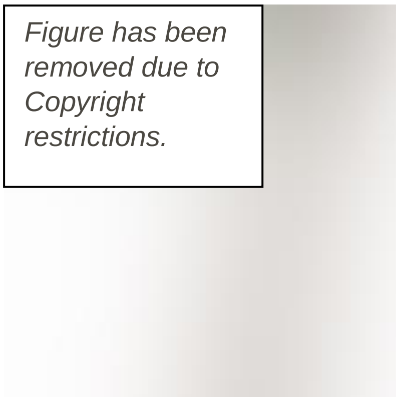


Figure 0.21(Kenhub)

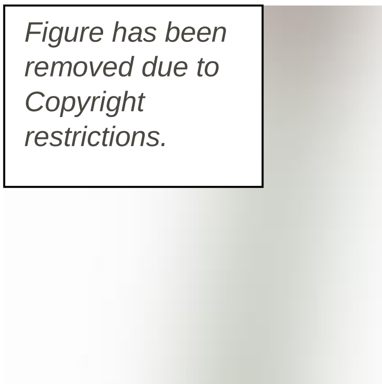
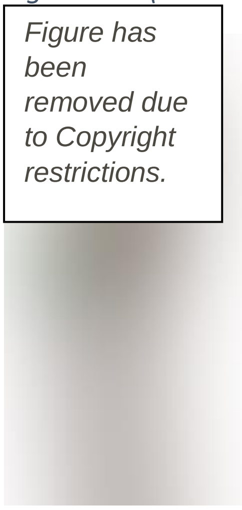


Figure 0.22(Kenhub)

<u>Origin</u>(Schellhas 1990)- origin of long head is through shared tendon on ischial tuberosity(medial impression)(Figure 0.21). At the lateral supracondylar ridge and at linea aspera of the femur, the other part i.e. short head originates (Figure 0.22)

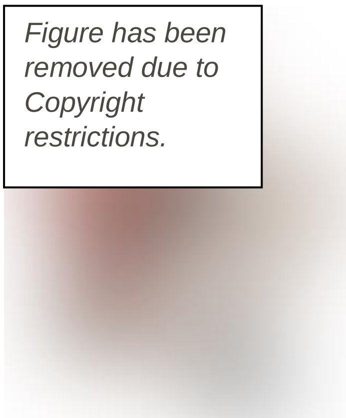


<u>Insertion</u>(Schellhas 1990)- An aponeurosis is formed by long head as it crosses the sciatic nerve and this aponeurosis is joined by short head. Aponeurosis is formed into a tendon. After that, this tendon is inserted into the fibula head (Figure 0.23)

Figure 0.23(Kenhub)

<u>Function</u>- knee flexion can be performed by both heads of biceps femoris. As the long head is attached to pelvis therefore it can produce hip extension. With the extended hip, biceps femoris long head gets weak in knee flexion and reason for that is active insufficiency. During flexed knee the long head gets weak in extension of hip due active insufficiency.

Iliopsoas



Two muscles, the inferior ends of iliacus and the psoas referred as iliopsoas (Figure 0.24). These two muscles cannot be identified as different in the thigh and they are different in abdomen.

Figure 0.24(Kenhub)

Origin- psoas major muscle has origin at the costal processes of the 12th thoracic vertebrae, all lumber vertebrae and from the body 1st to 4th lumber vertebrae(Figure 0.25)(Schellhas 1990).

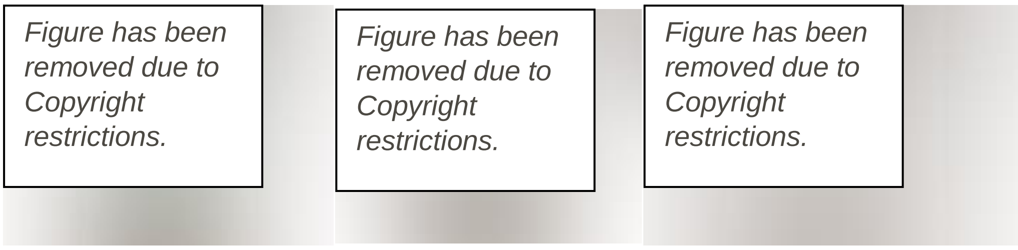


Figure 0.25(Kenhub)

Figure 0.26(Kenhub)

However, iliacus muscle has origin at iliac fossa (Figure 0.26).

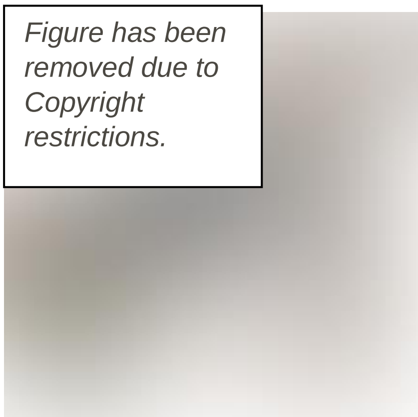


Figure 0.27(Kenhub)

Insertion- Both iliacus and psoas major inserts into lesser trochanter at femur(Figure 0.27)(Schellhas 1990).

Function- Iliopsoas is very important walking muscle because at hip joint it is the strongest flexor.

Gastrocnemius

In humans, at the back portion of lower leg there is strong bipennate muscle known gastrocnemius muscle (Figure 0.28). It is a superficial muscle and it have two heads just on the upside of knee. It runs from knee to the heel and join soleus muscle at Achilles tendon. Sometime soleus and gastrocnemius muscles are considered as single muscle known as triceps surae.

Figure 0.28(Kenhub)

Origin- The gastrocnemius has two heads at origin at medial condyle of the femur the medial head originates and from lateral condyle of the femur the lateral head originates.

Insertion- At Achilles tendon (calcaneal tendon) the muscle fibres of gastrocnemius and soleus muscle inserts. After that, into the heel bone or posterior area of calcaneus is the place where Achilles tendon inserts(Figure 0.29)(Schellhas 1990).

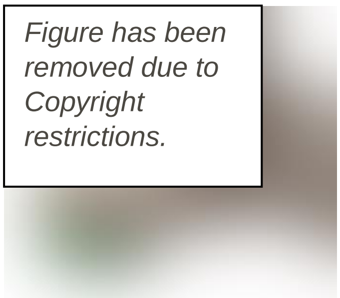


Figure 0.29(Kenhub)

Function- Gastrocnemius is considered as half of the calf muscle along with soleus. Therefore, at ankle joint it do plantarflexion and at knee joint it do flexion of leg. But gastrocnemius is mainly used in activities where fast movements of the leg take place i.e. during jumping, running.

Soleus

Figure 0.30(Kenhub)

At the calf soleus (Figure 0.30) is another powerful muscle lies below gastrocnemius muscle. It starts from just below the knee and ends at the heel.

Origin- soleus muscle has origin at upper fibula(Figure 0.31), tibia(Figure 0.32)(Schellhas 1990).

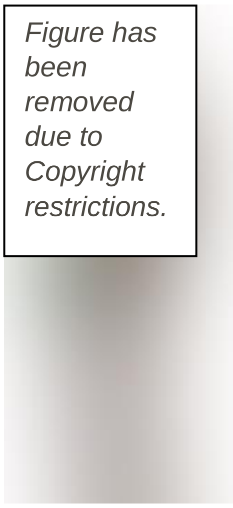


Figure 0.31(Kenhub)

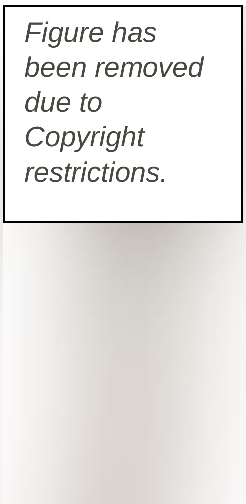


Figure 0.32(Kenhub)

Function-In walking, running and dancing soleus is important. It is used more in regular movement like walking unlike gastrocnemius which is used in fast movement of leg. When knee is in bent position the plantarflexion of ankle joint can be better done by soleus because its origin is on tibia unlike gastrocnemius which originates from femur. It is a calf muscle and it works to increase the angle between the leg and foot (ankle plantarflexion). Soleus maintains constant pull to stop the body from falling forward. It continually pushes the foot toe downward during stance and maintains the standing posture.

Tibialis anterior

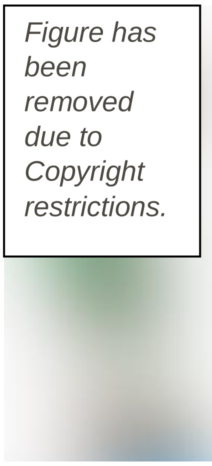


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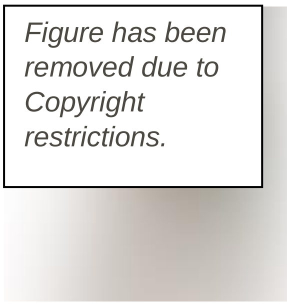
Figure 0.33(Kenhub)

tibialis posterior muscle (Figure 0.33) lies on the lateral side of the tibia and from upper part is fleshy and thick and lower part is tendinous.

Origin- It originates from upper half of lateral tibia and adjacent parts of interosseous membrane.



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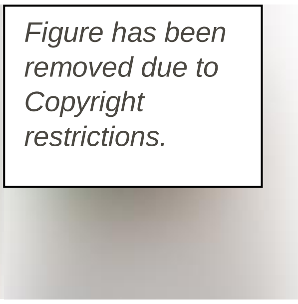

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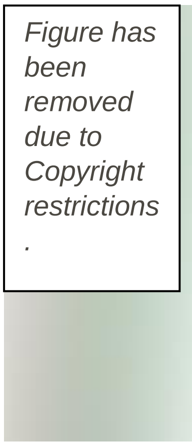
Figure 0.34(Kenhub) *Figure 0.35(Kenhub)*

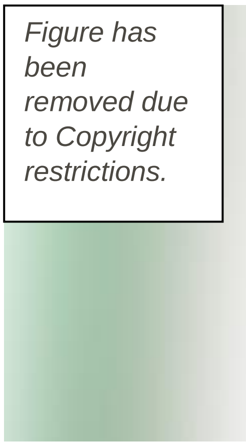
Insertion- Close to the ankle there is anteromedial dorsal aspect of the foot at this place fibres of tibialis anterior attaches to tendon. The tendon than inserts at 1st metatarsal bone base(Figure 0.34) and also at medial cuneiform bone(Figure 0.35)(Schellhas 1990).

Function- In the anterior compartment of the leg the most medial muscle is tibialis anterior. It foot can be dorsiflexed and inverted by this muscle. To tibialis posterior it can work as synergist as well as antagonist. Gastrocnemius and soleus are antagonist to tibialis posterior. As the foot strikes the ground during gait tibialis anterior eccentrically contract to stabilize the ankle and during swing phase it concentrically contract to clear the foot. When ball is kicked with foot it can be isometric ally contracted to lock the ankle.

Tibialis posterior

The most central muscle is tibialis posterior in lower leg. It is present deeply in the posterior part of the lower leg.





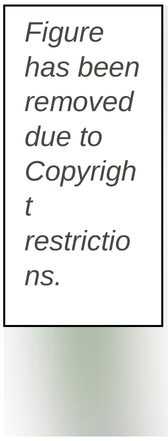


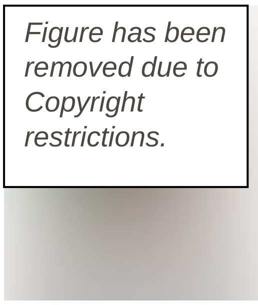
Figure 0.36 (Kenhub) *Figure 0.37 (Kenhub)* *Figure 0.38 (Kenhub)*

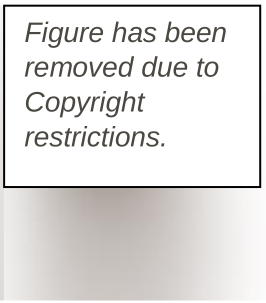
Origin- It have origin at inner-posterior boundaries of the fibula (Figure 0.36) and tibia (Figure 0.37). It have another attachment at interosseous membrane (Figure 0.38)(Schellhas 1990).

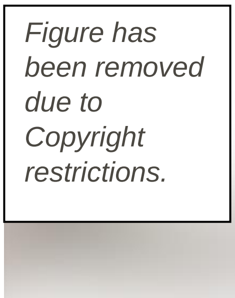
Insertion- the posterior tibial tendon is divided into three portion known as main, planter, recurrent. These portion attaches to different bone in foot (Figures 0.39)(Schellhas 1990).

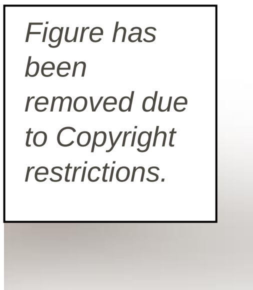
3 portions	attachments
Planter portion	The cuboid bone, the second and third cuneiforms, the bottoms of the second, third and fourth metatarsals
Main portion	First cuneiform and tuberosity navicular
Recurrent portion	Sustentaculum tali(calcaneus)

Table 0.1









Figures 0.39(Kenhub)

Function- The medial arch of foot is supported mainly by tibialis posterior. At ankle joint tibialis posterior can invert and help in plantarflexion of the foot. Overall it helps stabilization during walking.