An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance.

SAVIOUR ADJENTI (ADJSAV001)

Thesis Presented for the Degree of

DOCTOR OF PHILOSOPHY

In the Department of Human Biology, Faculty of Health Sciences,

University of Cape Town

Supervisors:

Prof. Graham Louw

Prof. Jennifer Jelsma

Dr. Marianne Unger

May, 2014

Declaration on plagiarism

I, SAVIOUR ADJENTI hereby declare that this thesis is my own work and has not been submitted for a degree at any other university. All the resources that I have used or quoted are acknowledged by a complete list of reference.

Name SAVIOUR ADJENTI

Signed ……..

Date ……..

Acknowledgements

Thanks to the Creator for all the people that came my way to bring this study to this point. I am highly indebted to my three supervisors in diverse ways. My vocabulary cannot thank them adequately enough. First of all, my deepest gratitude to Professor Graham Louw for providing all the necessary directions for the execution of this project. Indeed, I was more than fortunate to have you as my principal supervisor. The energy and alacrity with which you accorded to issues concerning me are unparalleled. Your ability to solicit for soft travel grants to conferences and funds for my general welfare are worthy gestures and have brought me this far. Thank you for everything! To Professor Jennifer Jelsma: what else can I say? I am grateful to you for allowing me to cross carpet from Basic Sciences to Rehabilitation Sciences to make this meaningful. Thank you dearly for making me to know the intricacies of statistical analysis. Indeed you have made me to become aware that research knows no limits. Your devotion to research, the support and guidelines toward the execution of this thesis is very much appreciated. How can I forget the personal grants for the training and use of the EMG equipment? I owe you a debt of gratitude for always having me on your agenda. To Dr. Marianne Unger, who am I and what is this thesis without you? Your being far away at Stellenbosch University Medical School did not deter you from attending to me always. Your time and the resources were always at my disposal. Thank you for driving me to all the sites designated for data collection and introducing me to the Physiotherapists and Clinicians involved. This made all the difference; I was readily accepted by all through your efforts. Your personal touch and encouragements in my valleys of despair contributed in no small ways to this thesis. Thank you for making me a "*besoeker"* at Tygerberg Teaching Hospital.

To Mr. Bruce Dando of the Technical and Support Unit of the Anatomy Division of the Department of Human Biology I owe you my sincerest gratitude. The transportation of the heavy and expensive equipment was made possible by you and your team. Folks like Deon, Charles, Vernon, Andrew, Bradley, Benedicts, and Mike of the Unit are worth mentioning for the manner in which you made the mornings of my data collection days light and easy. You guys are my heroes in the department!

To the managers of Faculty of Health Sciences International Postgraduate Funding Scheme, and The Faculty of Health Sciences Student Welfare Fund, thank you for making sure that the study did not come to a halt for lack of funding. To the faculty members who generously

supported my dreams through the raising of personal funds, I am most grateful for your acts of kindness.

To Associate Professor Fredrick Addai, Head of the Department of Anatomy, University of Ghana Medical School (UGMS), I owe profound gratitude for pushing my case all the way through to the relevant authorities. To the faculty and staff of the Department of Anatomy, UGMS I shall remain grateful for your prayers and support. Thanks to the University of Ghana for granting me the study leave.

To the immediate past Head of Department of Human Biology, FHS, UCT, Professor Lauriston Kellaway, thank you for being so keen on my case and ensuring that everything I requested was supplied and on time.

The Head of Human Research and Ethics Committee, Professor Marc Blockman and your team, I am most grateful to you for granting me ethical approval on time. Also a special thanks to Dr. Audrey Wyngaard of the Research Directorate of the Western Cape Department of Education, for the permission to execute this study in the schools. To my special participants and their parents, guardians and teachers of the various schools, you are the reason for this piece of work. Thank you for your willingness to go the extra mile. To the Principals, the Physiotherapists, Nurses and other health care providers and the staff of EROS, VISTA NOVA and FRIENDS DAY Specials schools as well as the Heads, teachers, staff and learners of Arcadia and Bergsig Primary & High Schools for opening your doors for this study. The two Heidi of Eros and Vista Nova as well as Neesa of Arcadia, hey ladies! you deserve a special mention and thanks for everything.

I owe a debt of gratitude to the teaching and non-teaching staff of the Department of Human Biology for your support, warmth and encouragement in diverse ways. Special thanks to Drs. Charles Slater and Delva Shamley for making me feel special always. A big thank you to Steve Steiner of the Imaging Unit for sorting me out with the EMG readings whenever I was lost, Steve, you are more than a pathfinder! To Dr. Asfree Gwanyanya for your warmth and support and for providing the special sphygmomanometer free of charge for the PCI test. Niri Naidoo and Gillian Ferguson thanks for granting me access to the equipment always and also for sharing your thoughts together on this journey. You ladies are brave!

Thank you to all colleague postgraduate students in the Department of Human Biology for your warmth and encouragement on this journey. Special thanks to Petra Maass for being my

occasional statistician and my friend and study mate Coenerad Hattingh of the Department of Psychiatry and Neuroscience for being there for me during those long practical sessions.

A big thank you to my Dad and siblings for tolerating me with the “no money” stories always. To my wife and our two sons, you guys were my source of energy; thank you for not hiding your disgust about my long absence from home but at the same time enduring it. I’m very grateful to you for all those telephone calls and e-mail conversations. To James and Ros Irlam & family of Rosebank East, I owe you a big thank you for giving me the privilege and opportunity to stay in the comfort of your home during the last stages of my study here in Cape Town. Thank you so much for this gesture.

Finally, special thank you to my Cadboll Residence mates as well as to Chris Mabeza & Peter Eze, for being like a family away from home to me. I am also indebted to all those whose toes I might have stepped, knowingly or unknowingly on this journey, thank you for being a cushion for me and not harming me back. My unreserved thanks to all who would have wished otherwise!

Abstract

Title: **An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance.**

Author: **Saviour Adjenti**

Date: **May, 2014**

Cerebral palsy (CP) is an abnormality in motor function and postural tone that usually occurs at an early age. Spastic type cerebral palsy (STCP) - the most common type of motor disorder – involves increased muscle tone, a rigid posture in the limbs and muscle weakness resulting in impairment of gross motor function, trunk instability and co-ordination. The management of CP cases includes a broad spectrum of therapeutic interventions, therefore involving a large multi-professional team, and providing an ideal opportunity for collaboration amongst professionals. The primary determinants of muscle function are the architectural parameters (MAP's) of the muscle which determine the macroscopic arrangement of muscle fibres relative to the axis of force generation.

Ultrasonography was used to quantify these MAP's while the NORAXAN® electromyograph was used to monitor neuromuscular activity in children and adolescents with STCP (N = 63) and the results were compared with the findings from aged-matched individuals with typical development (TD), (N = 82). All the muscles - external oblique (EO), internal oblique (IO), transversus abdominis (TrA) and rectus abdominis (RA) - were thicker in the STCP group than in the TD group. The EO, IO and TrA muscles in the STCP group were thicker at rest than in individuals with TD. The MAP's of EO, IO and TrA in the STCP group decreased when the muscles changed from the resting to an active state, as opposed to increasing in the TD group. The four muscles of individuals with TD and the RA of the STCP group showed significant changes ($p < 0.001$) in the frequency of EMG activity between the resting and active states. With regards to pennation, the abdominal muscles could be regarded as a transition group of muscles, lying somewhere between pennated and non-pennated muscle bellies.

The findings from this study revealed that the RA may be targeted during rehabilitation regimens in the provision of stability for the bony pelvis, however, the force generated by this muscle may not be sufficient for the maintenance of trunk stability without optimal support from the EO and IO. An elevated tone at rest in the EO and IO, coupled with unilateral activity of the RA may lead to mal-rotation of the bony pelvis.

The gross motor function measure (GMFM), which tested the five main domains of activity in individuals with STCP was well aligned with the gross motor function classification system (GMFCS) Levels (disability status) but did not correlate with changes in MAP's or with changes in the frequency of EMG activity between resting and active states. The performance of daily activities by individuals with STCP may not be a reflection of the activity of a muscle.

The physiological cost index (PCI) was performed as an outcome measure to determine and compare the level of energy consumption between the two groups. The participants with STCP consumed significantly more ($p < 0.001$) energy than the TD group. However, this test showed no association with MAP, EMG activity and the changes in these muscle parameters from resting to active states (*rho* ranged from -0.009 to 0.27 in the STCP group; *rho* ranging from -0.423 to 0.199 in the TD group). The PCI may not be a useful test in determining the morphological transformation taking place in a muscle or muscle groups.

The MAP's of the unaffected side of the abdominal muscles of the STCP individuals with hemiplegia showed similar characteristics to those of TD individuals. The STCP adversely affects the trunk musculature in a similar fashion to the limbs.

Knowledge of the macroscopic arrangement of the abdominal muscles is important in the management of pelvic stability in individuals with STCP.

Key words: spastic type cerebral palsy (STCP), abdominal muscles, postural muscles, muscle architectural parameters, muscle thickness, muscle fibre length, pennation angle, rehabilitation.

Table of Contents

Table of Tables

Table of Figures

List of equations

List of abbreviations and definitions

Abbreviation / Term	**Meaning / Definition**
Ac	Active state
AR	Assistant research
ASKp	Activities scale for kids, performance version
Bipedalism	Type of locomotion involving movement on two feet (Tobias *et al*., 1988)
CP	Cerebral palsy - a condition marked by impaired muscle coordination (spastic paralysis) and/or other disabilities, typically caused by damage to the brain before or at birth (Bax *et al.*, 2005)
Diplegia	Bilateral paralysis - weakness or impairment affecting the same body parts on both sides of the body
Diff	Changes between active and resting states
DPG	Diplegia
EMG	Electromyograph / electromyography
EO	External oblique
FL	Muscle fibre length / Fascicle length
GMFCS	Gross Motor Function Classification Scale
GMFM	gross motor function measure
Hemiplegia	A lateralised one-half of the body affected by weakness or paralysis
HEMIUNAFF	Hemiplegia unaffected side
HPG	Hemiplegia

ICC	Inter- / intra-class correlation coefficient
IO	Internal oblique
LT	Left side
MAP	Muscle architectural parameters
Monoplegia	A rare type of paralysis involving one limb
MPG	Monoplegia
Muscle architectural parameters	Includes muscle thickness, fibre length and pennation angle
Norm	Age-normalised parameter
PA	Pennation angle
PCI	physiological cost index
PI	Principal investigator
PODCI	Pediatric outcome data collection instrument
Quadriplegia	Tetraplegia – a weakness or paralysis involving all four extremities
R	Resting state
RA	Rectus abdominis
RT	Right side
sEMG	Surface electromyograph / surface electromyography
Schools: open, mixed or special	In this context: open schools are public schools; mixed schools cater for TD and STCP children; special schools are for STCP children.
Spastic paralysis	A feature of altered skeletal muscle performance in muscle tone involving hypertonia; may also be to refer to an unusual “tightness”, stiffness or “pull” of muscles (Palisano *et al.,* 2000)
STCP	Spastic type cerebral palsy
TD	Typically developing / typical development
Th	Muscle thickness
TrA	Transversus abdominis
Trunk stability	The ability to activate patterns of muscle co-ordination and posture to maintain balance, i.e. the keep the centre of gravity within the base of support (Moseley & Hodges, 2005).
US	ultrasonography / ultrasound

Chapter 1 Introduction

1.1 The scope of the study

Cerebral palsy (CP) by definition involves an abnormality in motor function and postural tone that is acquired at an early age (Palisano *et al*., 2000, Bax *et al*., 2005, Lichtwark & Wilson, 2007). In its most severe form, CP is associated with a complete lack of independent mobility (Dolk *et al.,* 2010). The condition is regarded mainly as a neurodevelopmental disorder with the highest rates in children living in low to middle income countries, including South Africa (Dowding & Barry, 1990; Dolk *et al.,* 2001; Sundrum *et al.,* 2005; van Toom *et al.,* 2007; Hjern & Thorgren-Jerneck, 2008). This presents as one of the motivations for the choice of subjects in this study – children and adolescents in a developing country. The incidence rate is increasing, possibly due to improved diagnostic techniques and test procedures (Dolk *et al*., 2010) and even in developed countries such as the United States of America, CP has been reported to be the most common motor disorder (Dolk *et al.,* 2001; Sundrum *et al.,* 2005; Odding *et al.,* 2006; Dolk *et al.,* 2010). Similar to other neurological disorders, CP is commonly associated with impairment of muscle function (Bernard *et al.,* 2009) but the mechanisms underlying the muscle impairment are not yet fully understood.

A few morphological studies on CP have revealed that the functional integrity of skeletal muscles in general, is associated with neuronal activity (Walker *et al.,* 1987; Brogren *et al.,* 1996; Lieber *et al.*, 2004). The nervous stimulation of large muscle groups such the hamstring and quadriceps femoris muscles have variously been investigated in support of this view (Verschuren *et al.,* 2008; Hussain *et al.,* 2013). However, little is known about the structure, function and neuronal activity of the abdominal muscles, which apart from the limbs muscles, are more often adversely transformed with the occurrence of CP (Lieber *et al.,* 2004; Malaiya *et al.,* 2007; Verschuren *et al.,* 2008; Hussain *et al.,* 2013). Therapists and researchers argue that this lack of information impedes the development of adequate therapeutic interventions aiming at the abdominal muscles (Rutherford & Jones, 1992; Maganaris & Paul, 2002; Barber *et al.,* 2012). Some researchers have raised concerns about the lack of an adequate theoretical basis and also about the lack of sufficient empirical evidence for the rehabilitation and management strategies involving physically and neurologically challenged individuals (Walker *et al.,* 1987; Brogren *et al.,* 1996; Lieber *et al.*, 2004). It has been suggested that a thorough knowledge of the perceived source of the

impairment in CP is required by clinicians and therapists in order to facilitate any intervention process (Burtner *et al.*, 1998). This is considered to be necessary since skeletal muscles, in general, have been reported to possess remarkable plasticity and can quickly gain or lose contractile material according to changes in loading regimens with a high capacitance for permanent disabilities with cases involving CP (Burtner *et al.,* 1998). According to Bernard *et al.* (2009) gaining an insight into the underlying mechanism of muscle impairment requires accurate measurements of the geometrical properties of the affected muscles.

It has been postulated that the abdominal muscles play an important role in stabilising the trunk and the provision of postural stability (Hodges *et al*., 2005; Malaiya *et al.,* 2007; Ohata *et al.,* 2008). It is envisaged that adequate knowledge of the geometry of abdominal muscle parameters may guide therapists in reducing the locomotor problems associated with this neuromuscular condition.

As a result of the bipedal nature of human beings, for the spine (vertebral column) to maintain stability, optimal control from all components of the neuromuscular system is required (Gans & Gaunt, 1991; Muramatsu *et al.,* 2002b; van Dieen *et al.,* 2003; Hodges *et al*., 2005). With the onset of CP and the pelvic tilt that usually accompanies the spastic type, it has been hypothesised that there may be adverse transformations in both the neural and muscular components of the individuals affected (Maganaris & Paul, 2002; Lieber *et al*., 2004; Hussain *et al*., 2013).

Therefore, in order to provide a better theoretical basis for the planning of rehabilitation interventions, involving the transformations of abdominal muscles with regards to CP, this study aims to:

- Identify whether abdominal muscles undergo transformation in children with CP
- Establish the nature of any such structural changes that may occur and
- Determine whether these changes impact on function.

1.2 Cerebral palsy (CP)

CP is defined as a non-progressive lesion in the developing brain which typically affects a child's movement and postural tone (Palisano *et al*., 2000; Bax *et al*., 2005; Rosebaum *et al*., 2007). Therefore, CP may be regarded as a central nervous system condition with a motor impairment component affecting mostly skeletal muscles (Morrel *et al.*, 2002). Children with

CP are reported to have various impairments that interfere with their activity and participation, which may be classified according to the International Classification of Functioning Disability and Health (ICF) into several categories / levels (Palisano *et al*., 2000; WHO-ICF, 2001; Ohata *et al.,* 2008). These impairments include neuromuscular and musculoskeletal problems such as spasticity, muscle contracture, lack of co-ordination, loss of selective motor control and weakness (Damiano *et al.,* 2000; Gormley, 2001). Even children with mild CP have been shown to demonstrate substantial weakness compared with their age-related peers of typical development (TD) (Damiano *et al.,* 2000; Barber *et al.,* 2011; Gough & Shortland, 2012). Spasticity is a common impairment in children with CP and the relation between higher resistance torque and lower strength is mainly determined by muscle morphology and neurological factors. In other words, it has been noted that most of these impairments have an associated musculoskeletal transformation which, in turn affects function / activity either directly or indirectly (Damiano *et al.,* 2000; Gormley, 2001). An increasing amount of research on CP in recent times, seeks to investigate the origin of the weakness and impairments (Lieber *et al*., 2004; Verschuren *et al.,* 2008; Hussain *et al.,* 2013). The present study focused on the muscular aspects of the abdominal muscles of children and adolescents with the spastic type, with regard to use or disuse of these muscles as a result of cerebral palsy.

Researchers have documented three main types of CP, with the spastic type (STCP) being the most common, and is characterised by hypertonia, hyperreflexia and constantly contracted tight muscles with stiff and difficult movements (Morrel *et al.,* 2002; Bax *et al.,* 2005; Rosebaum *et al.,* 2007). Consequently, the acronym STCP will be used from this stage of the dissertation onward, to represent the very subtype that is being investigated in the present study. From the morphological perspective STCP may be regarded as an upper motor neuron lesion with severe consequences on various skeletal muscles including those of the trunk. The other two types of CP, which are outside the scope of this study are the athetoid type, characterised by involuntary and uncontrollable movements and the ataxic type, characterised by a disturbed sense of balance and depth of perception (Chapman & Madison, 1988; Deluca, 1991; Deluca, 1996; Couper, 2002; Gage, 2004).

1.3 The role of abdominal muscles and the maintenance of pelvic tilt

As the abdominal muscles are relatively thin and as each has an individual action, their role with regard to the trunk is a subject of debate and an important area of research in biokinetics

(Woitiez *et al.,* 1984). There is evidence that the contribution of the abdominal muscles towards trunk and pelvis stability is decreased in children with STCP when compared with aged-matched children with TD (Hodges & Richardson, 1999; Hodges *et al.*, 2005). Children with STCP are reported to exhibit excessive abdomino-pelvic (anterior pelvic) tilt, and this has been associated with poor recruitment of abdominal muscles (Chapman & Madison, 1988; Mitsiopoulos *et al*., 1998; Richardson *et al*., 2002; Unger, 2011). Consequently, therapists target the abdominal muscles during rehabilitation activities in their bid to provide strength to this group of muscles and consequently improve the abdomino-pelvic tilt (Richardson *et al*., 2002; Hodges *et al*., 2005; Hodges, 2011). Studies by Unger (2011) to ascertain the effectiveness of these rehabilitative activities yielded some positive results. Hodges *et al.* (2005) intimated that abdominal muscles are the primary focus for therapists and clinicians in STCP, particularly those with anterior pelvic tilt. Ohata and co-workers (2008) noted that, regardless of which particular group of muscles is involved in anterior pelvic tilt, it is worthwhile to establish the degree of change in all muscles acting on the bony pelvis in order to understand the pathophysiology of one group or the other.

A study by Cholewicki *et al.* (2000) suggests that the degree of lumbar lordosis, pelvic tilt and abdominal muscle function are related to one another. Barrett & Lichtwark (2010), however, argued that there is no evidence of a relationship between abdominal muscle strength (function), lordosis and pelvic tilt and therefore all that could possibly occur is a posterior pelvic tilt with a concurrent decrease in the depth of lumbar lordosis. Subsequent to this publication many other clinical researchers suggested the use of modern *in vivo* imaging techniques to obtain empirical evidence on the subject of pelvic tilt, abdominal muscle involvement and function (Hart & Rose, 1986; Brogren *et al*., 1998; Barrett & Lichtwark, 2010; Unger, 2011). There has been increasing evidence that weakness of the abdominal muscles in children suffering from STCP is associated with anterior tilting of the bony pelvis (DeTroyer *et al.*, 1990; Brogren *et al*., 1998; Butler, 1998; Unger *et al.,* 2006). A search through literature on STCP and MAP's yielded a variety of reports on the exact role of trunk muscles with regard to pelvic stability and tilt with evidence from more recent publications that there may be both increased tone and weakness in the trunk muscles (Teyhen *et al*., 2008, Vasseljen *et al.,* 2009, Barrett & Lichtwark, 2010; Unger, 2011). In general, however, there is a paucity in the literature regarding the relationship between the anatomy and physiology of the abdominal muscles in children with STCP and the concomitant biomechanics and the effect on the trunk. This study seeks among other objectives to

determine whether there are differences in abdominal muscle activation between STCP and TD groups and whether children with STCP are predisposed to poor activation patterns with respect to EMG analysis.

1.4 Monitoring structure and function in the abdominal muscles

In order to establish the relationship between muscle architecture parameters (i.e. muscle thickness, pennation angle and fibre length), herewith referred to as MAP, muscle activation pattern and functional abilities of the child, it is necessary to have accurate measurement tools and there has been a call for an *in vivo* assessment, especially of changes in muscles due to STCP (Klimstra *et al.*, 2007; Benard *et al.,* 2009). Clinicians are of the opinion that, for a clinical method of assessing trunk muscles to be widely accepted, it must be relatively accessible to all with regard to cost to the patient and must also be devoid of potential harm to the patient and occupational hazards to therapists (Ohata *et al*., 2008; Vasseljen *et al*., 2009; Hodges, 2011). This study therefore took the use of ultrasonography to quantify the muscle architectural parameters of the abdominal muscles while surface electromyography (sEMG) was used to verify the degree of activity in these muscles in an attempt to meet safety standards in research and also in clinical practice (Higgins, 2006; Torloni *et al.,* 2009).

1.5 Quantification of muscle activity – EMG

The method of choice often used for recording the onset of muscle activity is electromyography (EMG), either by superficial or intramuscular wire electrodes (Tsao & Hodges, 2007; Vasseljen *et al.,* 2009). For the precise recordings of the onset of muscle activity at variable depths or muscle layers, Vasseljen and co-workers (2009) argued that intramuscular EMG is the better method. However, many researchers have agreed that the intramuscular method of assessing muscular activity is invasive and uncomfortable (Vasseljen *et al.,* 2009; Hodges 2011) and some investigators have suggested that it would be beneficial if non-invasive and less cumbersome alternatives to intramuscular EMG were available (Vasseljen *et al.,* 2006; Vasseljen *et al.,* 2009). As mentioned above, choice of surface electrode electromyography (sEMG) to measure muscle activity in this study is informed by several reasons. The non-invasive measurement of activity of motor units with sEMG is now used by clinicians for both the central and peripheral nervous systems (Vasseljen *et al.,* 2009, Prosser *et al.,* 2010). When comparing sEMG with needle EMG, the latter is considered to be the gold standard, yet the involvement of children in this study

makes it imperative to avoid being invasive. A major obstacle in applying sEMG, however, is that it is not possible to measure the spontaneous activity of denervated muscle fibres, which the conventional needle EMG is capable of doing with precision (Hodges & Richardson, 1998; Moseley & Hodges, 2005; Vasseljen *et al*, 2006). Despite these limitations, it has been used to measure timing and duration of output by the central nervous system, particularly in movement disorders such as dystonia and tremor (Hermens *et al*., 2000). A similar analysis using sEMG can be applied to analyse complicated movement patterns such as gait and gait disorders (Lauer *et al.*, 2007b; Vasseljen *et al.,* 2009). The combination of multiple sEMG derivations combined with for example an accelerometer gives a good visual representation of complicated movement disorders (Longmuir & Bar-Or, 2000).

Although sEMG has been reported to be useful only on a small set of suitable muscles, the study of propagation and other topographical aspects of voluntarily activated motor unit potentials (MUPs) along an array of electrodes potentially uncovers otherwise inaccessible physiological information (Longmuir & Bar-Or, 2000; Lieber & Friden, 2000). Therefore the use of sEMG to estimate muscle activity is noted to provide unique spatial information besides conventional MUP variables such as amplitude (Longmuir & Bar-Or, 2000; Lieber & Friden, 2000). In addition, the application of sEMG in neuromuscular biology certainly deserves further investigation because it is both noninvasive and patient friendly and therefore, was the method of choice to monitor the activation patterns in this study.

1.6 The use of ultrasonography

An alternative method for recording the onset of muscle is ultrasound imaging, which was first exploited in muscle activity of the myocardium by Heimdal *et al.* (1998). Work by Kremkau (2002) on ultrasound M-mode activity, showed that the result from the use of ultrasonography to monitor onset of muscular activity are comparable with recordings from intramuscular EMG detected in the lumbar multifidi muscles. Although the ultrasound M-mode was said to have detected the onset of muscle activity reasonably accurately, Stoylen *et al*. (2000) argued that it was relatively difficult to separate out the activity in muscles at different depths. These investigators therefore suggested that this is an inadequacy on the part of the use of ultrasound M-mode to determine muscle activity as compared to EMG usage. Studies showed in their work that all inadequacies notwithstanding, ultrasound use in quantifying the geometrical properties and MAP's of skeletal muscles is an acceptable

method, especially in children, due to its non-invasive nature (Walker *et al*., 2004; Klimstra *et al.,* 2007; Benard *et al.,* 2009).

1.7 Measurement of functional abilities

Functional abilities in children with STCP may be measured both in terms of the activities that the children can perform and the efficiency with which they are performed. Two simple outcome measures, namely gross motor function measure (GMFM) and physiological cost index (an indirect evaluation of oxygen consumption by functionally disabled individuals, PCI), are being used to relate MAP's to function in this study (Thomas *et al*., 1996; Avery *et al.,* 2003).

1.8 Functional activities

The functional abilities of children with STCP range across a wide spectrum and in order to establish a link between the structure and function of the abdominal muscles, a reliable and valid measure of functional ability needs to be identified. Although there are several measures of functional motor ability in children, such as "Peabody"," Bruininks-Oseretsky" and the "Movement A-B-C" (Russel *et al.,* 1989), the GMFM is the most widely used assessment of activity in children with CP (Russell *et al.,* 1989). It assesses the gross ability of children with CP in five dimensions, i.e 'Lie and Roll', 'Sit', 'Crawl and Kneel', 'Stand' and 'Walk, Run and Jump' and consists of eighty-eight test items (Russell *et al.,* 1989). The GMFM-66 is a condensed version of GMFM-88 with sixty-six test items that have been identified by Rasch analysis of the original GMFM-88 and arranged in order of item difficulty (Russell *et al*., 2000). The GMFM-66 gives an interval score of the overall level of activities, whereas the original GMFM produces a quasi-interval score (Russell *et al*., 2000). The GMFM-66 has been reported to have strong validity and reliability (Russell *et al.*, 1989; Russell *et al*., 2000).

1.9 Efficiency of movement: physiological cost index (PCI)

Physiological cost index uses heart rate as an indirect measure of energy (Raja *et al*., 2007). The PCI uses heart rate as an indirect measure of energy consumption and has been confirmed as a reliable index of the efficiency of gait, especially in children with CP (Raja *et al.,* 2007). The non-reliance on sophisticated equipment makes it a convenient measure of

energy consumption (Raja *et al.,* 2007). The PCI values are calculated based on the following formula (Equation 1):

$$\text{PCI} = \frac{\text{Final Heart Rate (beats/min)} - \text{Resting Heart Rate (beats/min)}}{\text{Speed of walking (metres/min)}}$$

The rationale for the use of PCI as a measurable objective is based on the hypothesis that weak abdominal muscles have poor recruitment patterns which is, in turn, being tested by the use of sEMG. The prediction is that this poor activation pattern will transfer a 'knock-on' effect onto the bony pelvis thereby resulting in a mal-alignment / imbalance or poor posture based on the understanding that all four abdominal muscles have made contacts with or attachments to the bony pelvis (Hodges *et al.,* 2003, 2005). As to whether this imbalance of the bony pelvis originating from the poor recruitment pattern of abdominal muscles will tilt the bony pelvis anteriorly or posteriorly is not yet clear. Assuming the hypothesis that weak abdominal muscles are characterized with poor recruitment patterns is true, then further predictions are that the resultant imbalance from the recruitment of abdominal muscles will translate to a transformation of the gait and cadence patterns. The negatively transformed gait and cadence patterns will lead to an increased demand of energy consumption during locomotion in order to compensate for the primary cause, which is the poor activation pattern of the abdominal muscles.

A measure of the PCI value is thus being used to determine this energy expenditure. Based on the anatomy of the bony pelvis and studies (Burtner *et al*., 1998; Damiano *et al*., 2000; Woollacott *et al.*, 2005) that relate the bony pelvis to a 'see-saw', it is expected that poor recruitment of abdominal muscles will shift the position of the moments of balance at the bony pelvis and thus translate to a high consumption of energy in walking. Therefore the development of poor MAP's and the exhibition of high PCI score may be considered to be indicative of the involvement of abdominal muscles in postural imbalance and pelvic instability / tilt. (Thomas *et al.,* 1996; Ohata *et al.,* 2008).

The instruments that were used in this study to measure MAP's included the use of ultrasonography to visualise the muscles' architecture, the use of electromyography to assess activation patterns in these muscles and the use of the gross motor function measure (GMFM) to measure function and, finally, the use of PCI to measure the efficiency of gait.

1.10 Statement of problem

The aforementioned basic morphological features of STCP and its associated complications underscore the fact that there is a plethora of research on STCP. However, most of this concerns the clinical and technical aspects, leaving a considerable gap in knowledge of basic muscle morphology and ultrastructural design. In addition, there are few if any papers which describe the characteristics of abdominal muscles in typically developing (TD) children. Filling this gap will assist researchers and physical therapists to understand fully and quantify the changes in the histo-architectural parameters of a muscle or muscle group as a common way of evaluating changes in muscle size in response to different types of training or immobilisation and / or interventions involved in spastic CP (Hodges *et al.,* 2005; Vasseljen *et al.,* 2009; Hodges, 2011). Again, most research on STCP targets only the limb muscles with relatively few attempts at trunk muscles, which are important in trunk stabilisation (Hodges *et al.,* 2005; Moreau *et al.*, 2009). To date, the role of the trunk in STCP, especially in lower limb function, is not clearly understood. This study will focus on the role of muscle architectural parameters (MAP) of the antero-lateral abdominal wall and their contributions to function and energy expenditure in gait in children with STCP.

There is a need for an *in vivo* estimation of architectural parameters and geometry of abdominal muscles in children (Zajac, 1989; Maganaris & Paul, 2002; Lichtwark & Wilson, 2007; Benard *et al.,* 2009; Unger, 2011). This may clarify some of the unanswered questions raised by Unger's work in which the role of the abdominal muscles in positioning the pelvis and the subsequent effect on lower limb function in children with STCP was investigated (Unger, 2011). The following questions emerged from that study, which in principle form the themes for the present study:

- How can the function of abdominal muscles in children be described and quantified in a non-invasive manner?
- How do the abdominal muscles in children with TD compare with children with STCP in terms of structure?
- Is there a relationship between activity in the abdominal muscles and function?
- What is the relative strength of the postural muscles and does weakness of trunk impact on gait patterns? (Unger, 2011).

1.11 Aims of study

This study explored the link between structure on ultrasound and function of the anterior abdominal muscles in children with spastic type of cerebral palsy using non-invasive techniques to estimate muscle morphology and activity. The technique of choice was ultrasonography, which is relatively inexpensive, fast, safe and a reliable means of assessment of *in vivo* structures. The functions of trunk muscles are expected to correlate with muscle structure in terms of activity and / or activation which was measured by electromyography. The indirect action of abdominal muscle function / activity was assessed through gross motor function measures (GMFM) and calculations of physiological cost index. The ultimate objective of this study was to determine the relationship between muscle architectural parameters (MAP) of abdominal muscle fibres (ultrastructure) with regard to the functional levels of children with spastic CP.

1.11.1 Specific objectives

The specific objectives of the study include the following:

- To validate ultrasonographic measurements of abdominal muscle thickness during resting and contracted states in children with STCP and in children from the typically developing (TD) group.
- To determine whether there is any significant difference in muscle fibre alignment / orientation (pennation angle) during resting and contracted states among children and adolescents with STCP and those from the TD group.
- To determine which of these MAP; muscle thickness, pennation angle and fibre length is most predictive of muscle activity / strength.
- To determine whether there is any significant difference in macroscopic muscle parameters (MAP) - muscle thickness, fibre length and pennation angle - in children with STCP across the different levels of CP, i.e. Gross Motor Function Classification Scale (GMFCS I, II, III & IV).
- To determine whether there is any significant difference in surface EMG activity in the abdominal muscles during resting and contracted states of children and adolescents with STCP and those from the TD group.
- To determine how MAP's relate to function in different age groups of children with STCP and the different ambulatory groups (GMFCS levels I, II and III) by assessing

the gross motor function measure (GMFM) among the three ambulatory groups of STCP.

- To determine whether there is any significant difference in energy consumption as measured by means of the physiological cost index (PCI) between ambulant children with STCP and TD children and whether there is any correlation between the PCI and architectural parameters of muscles between the STCP and TD groups.

1.11.2 Justification of study

It is generally accepted that the role of the core muscles, and specifically the abdominal muscles, is central to the maintenance of posture and balance. Weakness and poor activation of these muscles has been frequently reported in children with STCP. This study focused on the validity of muscle-thickness measurements with ultrasound imaging and other morphological variables of abdominal muscle, which enhanced our understanding of the structure and function of anterior abdominal muscles in children with STCP and TD children.

As yet, there have been few normative studies which have described the MAP's of TD children and the results of this study will provide data that can be used in future as a reference for comparison with children with different functional deficits.

In addition, a greater understanding of the differences between TD children and children with STCP may result in more targeted and effective rehabilitation intervention. For example, by analysing the relationship between structure and function, a better description of the relative influence of hypertonia and weakness was expected to emerge. This information might guide therapists in either targeting the reduction of tone and / or the strengthening of muscles as primary methods to improve function. This study may catalyse the process of evaluation of the existing rehabilitation procedures and designing of more comprehensive practices based on the foundation of basic knowledge in functional anatomy of muscles.

It was envisaged that the availability of ultrasonography and electromyography could be employed to further elucidate the link between structure and function of abdominal muscles, and specifically in this study, the anterior abdominal muscles in children with STCP. If found to be valid and reliable outcomes in the context of abdominal muscles in children with STCP, these measurement techniques could be used as objective outcome measures for intervention studies.

1.11.3 Plans for the execution of the study

Data collection fell under one of the following three broad areas:

- Anthropometric measurements which included height, weight, BMI, sex, diagnosis, GMFCS level,
- Measurements of the morphological/muscle architectural parameters (MAP) which included pennation angle, muscle thickness and muscle fibre length or
- Measurement of activity which included sEMG analysis, PCI evaluation and also measurement of GMFM scores.

The thesis will follow the following format: an introduction to cerebral palsy and the context of this study, a review of the relevant literature, the materials and methods relating to the research project, the data emerging from the study, a discussion of the results, and finally the reflections, recommendations and conclusions.

Chapter 2 Literature Review

2.1 The search strategy

The search strategies adopted for the review of this literature included searching through electronic databases of sites such as PubMed, CINAHL, COCHRANE, PEDro, PsychInfo, Science Direct, Africa Wide and Web of Science. The advanced search option was used for most of these databases. The key words employed in this search included such MeSH terms as: cerebral palsy, ultrasound, electromyography, pelvic tilt, muscle ultrastructure and gait together with the non-MeSH terms such as abdominal muscles, adolescents and children. The search strategy was extended as far back as to the 1980's, a period from which the use of ultrasonography and electromyography began to gain interest amongst clinicians and researchers. Having covered the topics thoroughly and due to obvious time constraints, the search strategy was finally restricted to those articles available in the English language only.

The use of the Boolean logic commands, namely: AND / OR / NOT were observed to either include or exclude some of the terms, with alternative terms being issued at some instances. For example, trunk muscle was sometimes used in addition to abdominal muscles in some of the databases. Irrespective of the rigorous search strategy employed, many of these databases yielded large volumes of irrelevant data. The relevant articles obtained from the search strategy were analysed and reviewed in subsequent sections of this chapter.

2.2 Brief overview of the chapter

The topic of the research is the relationship between the structure of the abdominal muscles in children with spastic type cerebral palsy (STCP) and typically developing (TD) children and how the structure is related to the functioning of the child. Damiano (2006) proposed that, in order to test muscle function, strength and posture in children and adults with STCP, a research paradigm has to be developed which emphasises the basic architecture and physiology of skeletal muscles. The abdominal muscles are of particular interest as they are thought to play an important role in posture and balance.

This chapter therefore starts with an overview of the structure of the abdominal muscles in typically developing individuals, the structure of the bony pelvis and its role in trunk stability, and a description of pelvic tilt and the internal architecture of abdominal muscles. Attention is then turned to cerebral palsy (CP) and the impairments and activity limitations that are most common. The following section explores research done on the morphological aspects of

skeletal muscles with regards to CP. A short appraisal of some of the important studies identified for this project, particularly the methodologies used and how these studies inform the choices of equipment and procedures used for the present study are included. The protocol used for searching the literature for this review is broad enough to cover any morphological work done on CP and skeletal muscles in any part of the body for children through to adults; although this study is limited to the abdominal muscles of children and adolescents. A broader search strategy was employed in order to give a sound understanding of the subject matter, namely the degree of morphological transformation seen in skeletal muscles as result of CP and its associated effect with activity and function.

2.3 The anatomy and function of skeletal muscles

The primary function of the skeletal muscle is to provide torque / force for movement and specifically for the maintenance of upright posture (Gans & Gaunt, 1991; Andersson & Mattson, 2001). The word muscle is considered to be used at three different levels in the human body - the tissue level, organ level and the system level (Andersson & Mattson, 2001; Goh *et al*., 2006). However, the functions of each of these levels are reported to be different but interrelated (Andersson & Mattson, 2001; Damiano *et al.*, 2000). The term muscle tissue is therefore regarded as the active component of the muscle organ (Andersson & Mattson, 2001; Goh *et al*., 2006) since the phrase muscle tissue is reported to have a direct stimulation from the nervous system (Ferreira *et al.,* 2004; Urquhart & Hodges, 2005). It is from this consideration that the evaluation of electrical activity through the EMG test in the abdominal muscles is included in the present study.

A muscle tissue is said to comprise of a group of muscle cells often called muscle fibres (Brooks & Faulkner, 1988; Muramatsu *et al.*, 2002b) and these are further divided into myofibrils (Jones *et al.,* 1997). The myofibrils in turn have been found to comprise of a series of structures called sarcomeres (Brooks & Faulkner, 1988; Jones *et al.,* 1997). In essence, the sarcomere is described as the smallest functional unit of a muscle tissue (Jones *et al.,* 1997; Muramatsu *et al*., 2002a). It is at the functional level that the protein myofilaments (actin and myosin) are located (Jones *et al.,* 1997).

It has been reported that connective tissue is an integral component of skeletal muscles at the organ level (Palastanga *et al*., 2009). The connective tissue component in a muscle, however, is regarded as passive because its force production does not occur as a result of nervous stimulation (Chapman & Madison, 1988; Deluca, 1991; Maganaris *et al.,* 1998).

Although the present study is regarded as an ultrastructural investigation, the instrumentations used do not transcend to the cellular level. Therefore the findings obtained are a trajectory of that which is presumed to be the ideal situation at all levels of a muscle, taking into consideration the fact the functions at all levels of a muscle are well coordinated (Getchell *et al.,* 2005; Rivilis *et al*., 2011).

2.3.1 The properties of skeletal muscles

Muscles in general are said to be characterised by some unique qualities (Kremkau, 2002; Vasseljen *et al.,* 2006; Vasseljen *et al.,* 2007). The aim of any therapy, palliative or rehabilitative, is to enhance these properties for optimum function (Richardson *et al*., 2002; Damiano *et al*., 2000). There has been a suggestion that a neuromuscular condition such as cerebral palsy is capable of altering all or some of these properties of a skeletal muscle (Richardson *et al*., 2002; Damiano *et al*., 2000). The following have been described as the properties of muscles in general:

(1) Excitability or irritability – the ability to respond to chemical stimuli by producing electrical signals (action potential)

(2) Conductivity – The ability to propagate the action potential along the plasma membrane

(3) Contractility: - The ability to shorten in response to a stimulus and become able to generate force to do work. (Unique property - only to muscle).

(4) Extensibility: - The ability to stretch, and

(5) Elasticity: - The ability to regain shape (Muramatsu *et al.,* 2002b; Moore *et al.,* 2005).

The properties of extensibility and elasticity have been considered as conferring mechanical qualities on skeletal muscles and thus allow them to be adaptable to forces that act on them (Fukunaga *et al.*, 2001; Moore *et al.,* 2005; Lichtwark *et al.,* 2007). Frequently the administration of a rehabilitation programme and / or chemotherapy, directly or indirectly improves the contractile, extensible and elastic properties of muscles (Muramatsu *et al.,* 2002).

It is anticipated that this study would evaluate the extent of transformation of these properties in abdominal muscles in children with STCP when compared with individuals from the TD group.

2.3.2 Skeletal muscles and force production

There are numerous factors that have been reported to affect the force output of a muscle. These are generally grouped into three categories, namely (i) physiological, (ii) neural, and (iii) biomechanical (Panjabi *et al*., 1989; Muramatsu *et al.,* 2002b; Legerlotz *et al.,* 2010).

The physiological factors which include (a) the physiological cross-sectional area (PCSA), representing the number of force-generating units or myofibrils that are lying parallel in a muscle (discussed below) and (b) the muscle fibre types (Moore *et al.,* 2005; Legerlotz *et al.,* 2010). Due to logistic and ethical concerns in the current study, the physiological factors did not form part of the measurable objectives. Additionally, with regard to PCSA, a number of research projects centred on limb muscles in individuals with STCP have already been completed, and hence the current study focused on the understanding of the neural and biomechanical factors of the abdominal muscles.

Neural factors include (i) muscle fibre activation. The general consideration is that the more fibres that are activated, the greater the maximal force that the muscle can produce by a muscle (Bergmark, 1989; Richardson *et al*., 2002) and (ii) the rate of activation of the motor units (Rose & McGill, 2005). With this, it has been noted that as the frequency increases so does the force of activation (Bergmark, 1989; Richardson *et al*., 2002). It is based on the consideration of the neural factor in the production of force of a muscle that has informed the inclusion of the investigation of the EMG activity in this study.

The third general factor considered to influence the production of force of a muscle is biomechanical which is related to the structure and function of skeletal muscle (Hodges *et al*., 2003; Aggeloussis *et al.,* 2010). This is the main target of the study. Information on the architecture is reported to be essential for the study of function since muscle architectural parameters (MAP) have significant effects on the force-generating capacity of a muscle (Narici, 1996). The architectural parameters of a muscle can also be used to set up the neuro-musculoskeletal models for the investigation of human movement (Lictwark *et al.,* 2007). The principal theme of this study is the biomechanical factors affecting force production of the abdominal muscles.

Muscle architecture primarily refers to the arrangement of muscle fibres in muscle tissue / organ and overall muscle thickness (Abe *et al.,* 1999; Narici, 1999; Lieber & Friden, 2000; Muramatsu *et al.,* 2002). Using this view, muscles may be grouped into two basic types: pennate and non-pennate muscles (Lieber & Friden, 2000). A non-pennate muscle is described as one in which the muscle fibres run parallel to the line of pull of the muscle, such that the fibre is in the direction of the overall muscle vector (Lieber & Friden, 2000; Aggeloussis *et al.,* 2010).

On the other hand, a muscle with pennate arrangements is regarded as one in which the muscle fibres run diagonally with respect to the line of pull of the muscle (Abe *et al.,* 1998; Naciri, 1999; Lieber & Friden, 2000). The angle formed between the line of pull and the alignment of the muscle fibres is referred to as the pennation angle (Fukunaga *et al.,* 1997; Lieber & Friden, 2000; Binzoni *et al.,* 2001). The advantage of the pennate arrangement has been reported to be an increased force output as a result of the increased amount of contractile material per unit volume (Binzoni *et al.,* 2001; Shortland *et al.,* 2002). Although more force is reported to be produced by a pennate muscle, not all the force is transmitted to the tendon (Hodges & Richardson, 1995a; Binzoni *et al.,* 2001; Infantolino & Challis, 2010). The amount of force transmitted decreases with increases in the angle of pennation (Hodges & Richardson, 1995a; Binzoni *et al.,* 2001; Infantolino & Challis, 2010). In a non-pennate muscle there is a greater range of movement than pennate muscles on contraction (Binzoni *et al.,* 2001).

Studies have shown that the two structural components of a skeletal muscle namely the muscle and connective tissues influenced the force-length component of the biomechanical means of the generation of a muscle force (Maganaris & Baltzopoulos, 1998; Klimstra *et al.,* 2007). Muscle fibres are reported to produce their greatest force at a length slightly greater than their resting length (80 – 120%) (Binzoni *et al.,* 2001).

As a muscle fibre is shortened to a length that is less than this, force output is noted to decrease considerably due to overlap of the myosin and actin filaments (Maganaris & Baltzopoulos, 1998; Binzoni *et al.,* 2001). This overlap may then result in an increase in muscle thickness.

2.3.3 The influence of MAP's on muscle strength

According to Kawakami *et al*. (1995) muscle power is different from muscle strength. Muscle strength is described as the amount of force that the muscle can produce and is often referred to as muscle force while muscle power denotes the maximum force per unit time that a muscle is capable of generating, with muscle velocity being commonly used to relate to muscle power (Kawakami *et al.,* 1995; Fukunaga *et al*., 1997; Wakahara *et al*., 2012). The production of muscle force or muscle strength is also linked to other factors such as muscle fibre composition, neural activation (Brainerd *et al*., 2005, Fukunaga *et al.,* 2006) and the pennation of the muscle fibres, as discussed above. However, muscle thickness has been the most frequently considered component of the MAP's as having the strongest influence on muscle strength (Kawakami *et al*., 1995; Lieber & Friden, 2000; Shortland *et al*., 2002, 2006, Ohata *et al.,* 2008 & Wakahara *et al.,* 2012).

Several researchers into muscle ultrastructure indicate that, for a given anatomical cross-sectional area and volume of a muscle, an increased pennation angle leads to a reduced muscle fibre length, allowing more contractile material to be placed in parallel, thereby increasing the maximum force that a muscle is capable of generating (Yue *et al.,* 1994; Wakahara *et al.,* 2010). According to Maganaris *et al.* (1998) the maximum force produced at a given muscle fibre length in the direction of the fibres in a pennate muscle is higher than the maximum force produced in the direction of the fibres of a parallel muscle of the same anatomical cross-sectional area and volume. With regard to MAP, the pennation angle is said to change inversely as a function of muscle fibre length and proportionally as a function of the isometric force generated by the muscle so that the fibre volume, represented also by muscle thickness, is kept constant at different lengths and contracted stages (Yue *et al.,* 1994; Narici *et al*., 1996; Maganaris *et al.,* 1998; Wakahara *et al.,* 2010). Moreau *et al.* (2010) similarly noted that the angle of pennation of a muscle is inversely related to the force and shortening velocity, such that the greater the pennation angle, the lesser the force that is transmitted to the tendon and consequently the lesser the shortening velocity. This is, however, in contrast to the a study by Kawakami *et al.* (1993) in which they noted that the effect on force production by a muscle is usually offset by the fact that a larger pennation angle allows more contractile material to be attached within a given volume.

Reports by Moreau *et al*. (2010) indicated that, the number of sarcomeres of a muscle reflected by its size or thickness is directly proportional to the amount of force that the

muscle can produce. These workers further showed that, the number of sarcomeres in series is reflected by the length of the muscle fibres and this in turn is directly related to the maximum shortening velocity and the range of movement of the muscle (Moreau *et al.,* 2010).

2.4 Overview of the anatomy of the abdominal muscles in a typically developing individual

Although the abdominal muscles constitute the musculature of the anterior, lateral and posterior abdominal walls, in the context of this study, use of the term refers to the four pairs of muscles forming the anterior abdominal wall (Fig 1), namely the rectus abdominis (RA), external obliquus abdominis or simply as external oblique (EO), internal obliquus abdominis or internal oblique (IO) and transversus abdominis (TrA). The structure is discussed here and the functioning in the subsequent section.

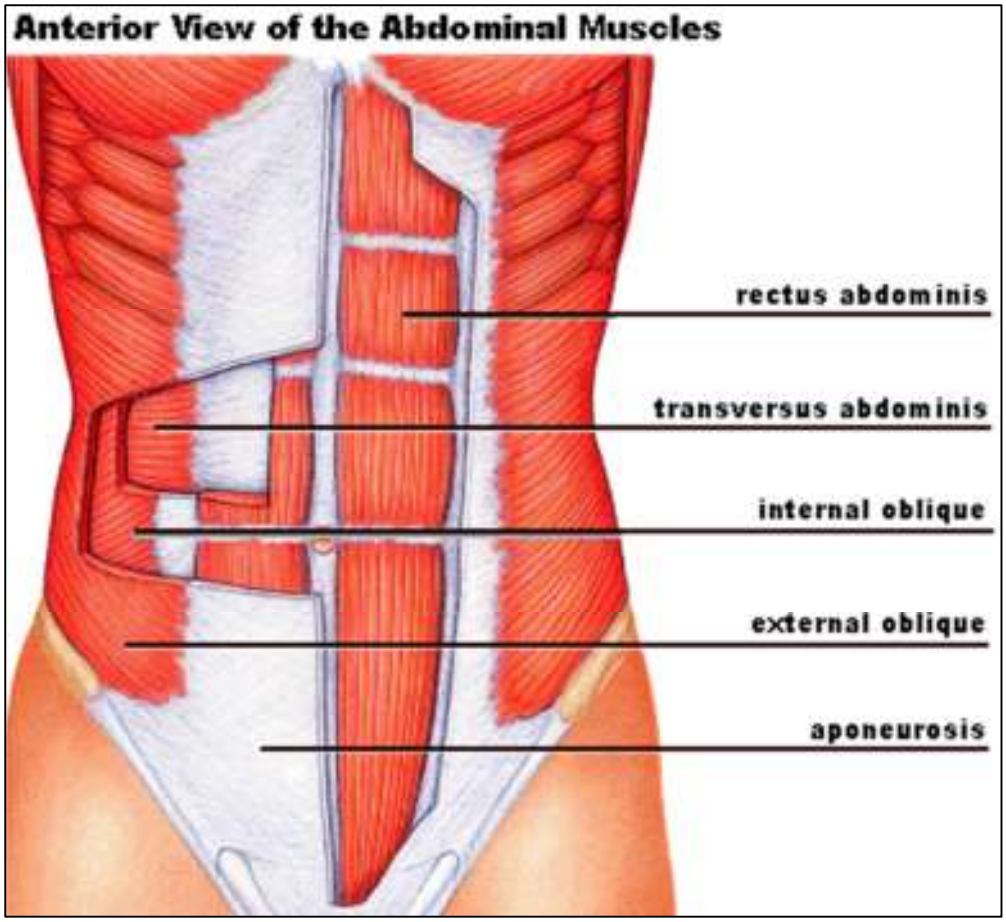


Figure 1: Diagram showing muscles of the anterior anterolateral abdominal wall
Source: http://www.yorku.ca/earmstro/images

2.4.1 Rectus abdominis muscle (RA)

Rectus abdominis (RA) is broad, strap-like (see Figure 1 above) and separated from its fellow from the opposite side by the linea alba – a dense sheet of connective tissue (Tobias *et al*., 1988; Hodges, 1999; Standring *et al*., 2005). Theoretically therefore, RA is made up of parallel muscle fascicles which may allow the production of only small forces yet enable a wide range of movements (Hodges *et al*., 2003; Moses *et al*., 2005). The inferior attachments of RA is on the upper edge of the pubic symphysis and the pubic crest accounting for its probable engagement in anterior pelvic tilt in the case of individuals diagnosed with STCP (McGill, 1996; Hodges, 1999; Moses *et al*., 2005; Ohata *et al*., 2008). Superiorly, RA is attached anteriorly on the xiphoid process and the cartilages of ribs numbers seven, six and five (Snijders *et al*., 1995; Cresswell *et al*., 2002; Standring *et al*., 2005; Ohata *et al.,* 2008). The main action of RA is to flex the vertebral column and assist in all expulsive acts by compressing the abdominal viscera (Snijders *et al*., 1995; Hodges, 1999; Cresswell *et al*., 2002; Standring *et al*., 2005; Ohata *et al.,* 2008). Both rectus abdominis muscles are thought to cause anterior tilting of the pelvis upwards when the thorax is fixed (Campbell, 1991; Hodges, 1999).

The pyramidalis muscle is reported to be a small, triangular muscle that lies anterior to the lower part of the RA within the rectus sheath in some individuals (Standring *et al.*, 2005). However, in this study the pyramidalis muscle has been excluded because it is inconstant and also owing to the fact that the physiological significance of the contribution of this muscle to the anterior abdominal wall remains doubtful (Moses *et al.*, 2005; Standring *et al*., 2005).

2.4.2 External Oblique (EO) muscle of the anterior abdominal wall

The external oblique (EO) muscle lies on the anterolateral side of the torso (Figure 2) with a flat, fleshy belly laterally and becomes aponeurotic as it approaches the RA on the medial side (DeTroyer *et al*., 1990; Campbell, 1991; Standring *et al*., 2005). The fibres of EO run inferiorly and anteriorly (shown by arrows in Figure 3) with its superior attachments terminating as digitations on the lower eight ribs, about a handbreadth from the edge of the sternum and costal margins (Campbell, 1991; Hodges, 1999; Cresswell *et al*., 2002; Standring *et al*., 2005; Ohata *et al.,* 2008). Inferiorly, the posterior fibres of EO run almost vertically to attach to the outer lip of the anterior half of the iliac crest. The remaining fibres are directed inferiorly and anteriorly (Figure 3) with the most inferior portion folding back on itself to form the inguinal ligament, which runs between the anterior superior iliac spine and

the pubic tubercle (Campbell, 1991; Hodges, 1999; Standring *et al*., 2005). Anteriorly, the aponeurosis of EO inserts onto the linea alba and posteriorly the EO does not make any contact with the vertebral column (Campbell, 1991; Hodges, 1999; Standring *et al*., 2005; Ohata *et al*., 2008).

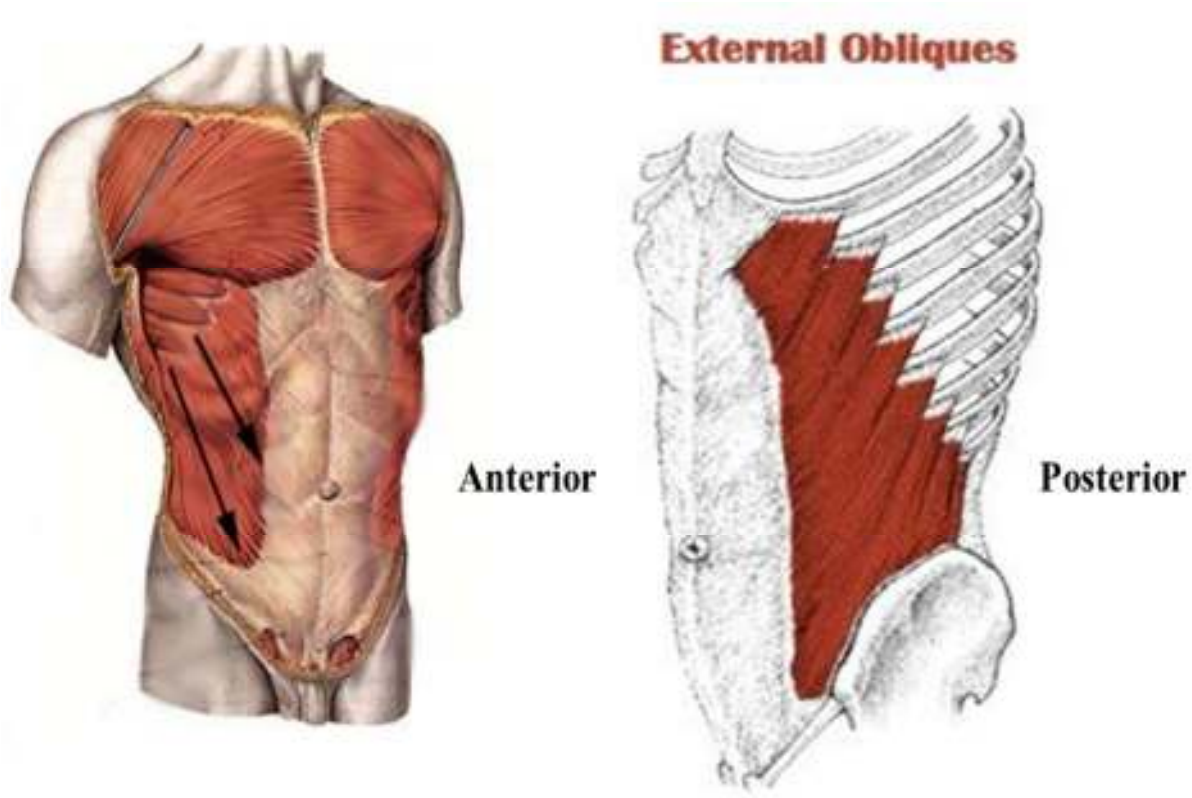


Figure 2: Diagrams showing the orientation of the external oblique fibres (arrows) and attachment to the bony pelvis (right)
Adapted from: http://www.yorku.ca/earmstro/images

Functionally, EO is noted to be involved in the compression of abdominal viscera and thus helps in expulsive acts when the thorax and pelvis are fixed (Williams *et al.*, 1989; Hodges, 1999). Secondly, with the pelvis and vertebral column fixed, EO is said to draw the thorax downwards and as such aids in forced expiration (Hodges, 1999; Standring *et al*., 2005; Ohata *et al.,* 2008). Unilateral contraction of EO while the pelvis alone is fixed, flexes the trunk laterally and rotates it to the opposite side, while both muscles flex the trunk (Snijders *et al.,* 1995; McGill, 1996; Hodges, 1999; Standring *et al*., 2005; Ohata *et al*., 2008). Both muscles, have been reported to cause the front of the pelvis to tilt anteriorly and flex the trunk when the thorax alone is fixed (Snijders *et al*., 1995; McGill, 1996; Hodges, 1999; Ohata *et al*., 2008).

2.4.3 Internal Oblique (IO) muscle of the anterior abdominal wall

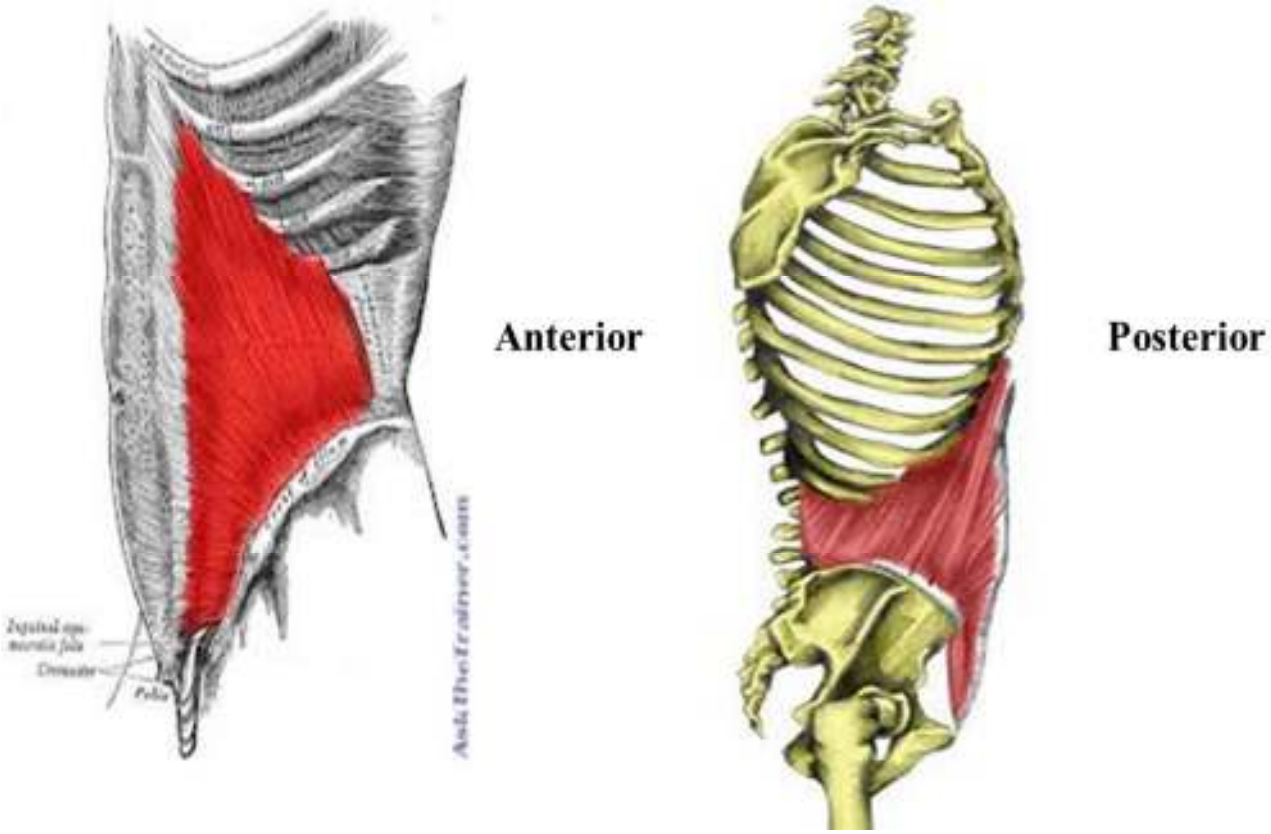


Figure 3: Diagram of the internal oblique muscle showing the orientation and attachment of fibres
Source: http://www.teachpe.com/images/muscles./google.co.za/images

The fibres of IO run superiorly and anteriorly (Figure 3) at right angles deep to those of the EO (Hodges, 1999; Standring *et al*., 2005). Postero-inferiorly it has some of its fibres attaching to the thoracolumbar fascia (Figure 4 - right), through which it gains attachment to the lumbar and thoracic parts of the vertebral column (Snijders *et al*., 1995; McGill, 1996; Hodges, 1999; Standring *et al*., 200; Ohata *et al*., 2008). The remaining fibres attach to the intermediate lip of a large part of the anterior half of the iliac crest and the lateral half of the inguinal ligament (McGill, 1996; Hodges, 1999; Ohata *et al*., 2008), even though Acland

(2008), demonstrated that this attachment does not exist. The superior fibres attach anteriorly and posteriorly to the lower three or four costal cartilages (Figure 4), while the intermediate fibres run superiorly and anteriorly, become aponeurotic and insert on the linea alba (McGill, 1996; Hodges, 1999; Ohata *et al*., 2008). The anterior or inguinal fibres arch medially and inferiorly, become aponeurotic, and unite with the corresponding fibres of the transversus abdominis (TrA) to form the conjoint tendon, which continues on to attach to the medial part of the pectin pubis, anterior edge of pubic crest and linea alba (Snijders *et al*., 1995; McGill, 1996; Hodges, 1999; Standring *et al*., 2005; Ohata *et al*., 2008). The functions of IO are similar to those of EO except that upon fixing the bony pelvis IO flexes the trunk and rotates it to the same side (Hodges, 1999; Ohata *et al*., 2008).

2.4.4 Transversus abdominis muscle (TrA)

Fibres of TrA run transversely in an anterior direction deep to IO and become aponeurotic along a curved line which is concave anteriorly (Figure 5) such that its aponeurotic part is widest opposite the umbilicus (Campbell, 1991; Hodges, 1999; Ohata *et al*., 2008). Posteriorly, TrA gains attachment to the lumbar vertebra through the thoracolumbar fascia (Snijders *et al*., 1995; McGill, 1996; Hodges, 1999; Ohata *et al*., 2008). Some of its posterior fibres arise from the internal surfaces of the lower six costal cartilages and interdigitating with the diaphragm, while yet others arise from the anterior half of the iliac crest (Figure 5) and the lateral third of the deep surface of the inguinal ligament (Snijders *et al*., 1995; McGill, 1996; Hodges, 1999; Ohata *et al*., 2008). Anteriorly, most of its aponeurotic fibres insert onto the linea alba medially while the inferior or inguinal fibres become aponeurotic, fusing with corresponding fibres of IO to form the conjoint tendon (McGill, 1996; Hodges, 1999; Ohata *et al*., 2008). The main action of TrA is in compression of abdominal viscera and also in the stabilisation of the lower trunk (Hodges, 1999; Standring *et al*., 2005; Ohata *et al*., 2008).

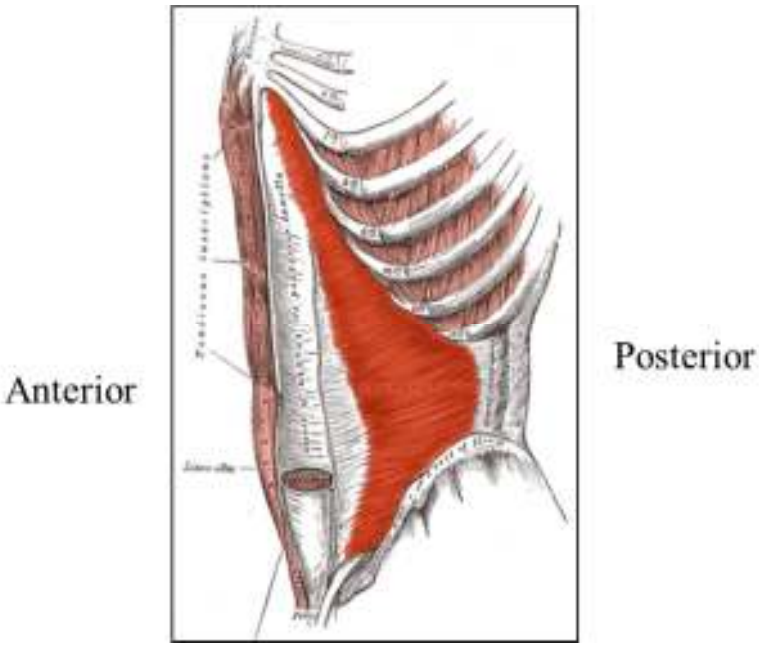


Figure 4: Diagram showing the orientation and attachments of the transversus abdominis muscle. NB: The EO and IO muscles have been reflected
Source: http://www.teachpe.com/images

All four abdominal muscles play a role in enclosing and protecting the organs housed in the abdominal cavity and false pelvis (Standring *et al*., 2005). In addition, they alter intra-abdominal pressure and can be used for forced expiration (Moses *et al.,* 2005; Standring *et al*., 2005).

The function of the RA is described as flexion of the vertebral column based on the direction in which the muscle bellies run (Moses *et al.,* 2005; Standring *et al*., 2005). The actions of the EO and IO have often been associated with rotation of the trunk in forced inspiration based on the orientation of these muscles (Moses *et al.,* 2005; Standring *et al*., 2005) whereas the TrA has been reported to be involved in the compression of abdominal viscera (Moses *et al.,* 2005; Standring *et al*., 2005).

It has been noted that the biomechanical effects of these abdominal muscles when in concentric action produce moments at the bony pelvis (Cholewicki *et al.,* 2000; Richardson *et al.,* 2000). According to Tobias *et al*. (1988) the physiological and biomechanical forces being directed to the bony pelvis are capable of shifting the equilibrium position of the trunk either anteriorly or posteriorly. Recent evidence has shown that investigators and physical therapists have implicated all the four abdominal muscles in the maintenance of posture and balance to the trunk (Hodges & Richardson, 1999; Hodges, 1999; Cholewicki *et al*., 2000).

Voluntary head and neck movements as well as movements in the limb musculature have been reported to have sequential contractions on the abdominal muscles which, in turn produce rotatory forces at the pelvis (Richardson *et al.,* 2002; Teyhen *et al.,* 2008; Clark *et al.,* 2011). Prior to the recent involvement of all the four abdominal muscles in the maintenance of posture and stability of the trunk, knowledge in this regard has been limited to the TrA based on the interdigitation of its fibres with the thoracolumbar fascia (Moses *et al.,* 2005; Standring *et al*., 2005).

The abdominal muscles are generally considered to be weaker in children in whom the fleshy belly to aponeurotic ratio is reportedly smaller than in adults (Moses *et al.,* 2005; Standring *et al*., 2005; Teyhen *et al.,* 2008). The exaggerated pelvic tilt in infants has generally been associated with the under-development of abdominal muscles (Viaz *et al.,* 2002; Khamis & Yizhar, 2007) as this tilt is reported to disappear during late childhood to adult life in TD individuals (Viaz *et al.,* 2002; Khamis & Yizhar, 2007).

In general, the various muscles of the anterior abdominal wall receive both motor and sensory innervation from the ventral rami of the seventh to twelfth thoracic (intercostal nerves, T7 – T12) together with the ventral ramus of the first lumbar (L1) nerve (Standring *et al.,* 2005). It is therefore generally assumed that abuses to the developing brain, which adversely affect the cortical regions receiving input and output from the T7 to L1 segments of the spinal cord, could potentially alter the structure and function of the musculature of the anterior abdominal wall (Standring *et al.,* 2005). Variations in the structure and function of the various abdominals muscle have also been documented (Moore *et al.*, 2005; Acland, 2008).

There has been reports of individuals with STCP who are unable to maintain a sitting posture, and also with whom ambulation becomes a near impossible status, and found to have weak abdominal muscles (Hodges & Richardson, 1999; Ohata *et al.*, 2008). Some of these observations coupled with this this brief anatomical description of the abdominal musculature shows that there is a connection between the anterior portion of the trunk and the bony pelvis. Whether these linkages by way of weak ligaments and poorly defined muscle-to-bone aponeurotic attachments are capable of transforming the posture of an individual with alterations in the central nervous system with the resultant show of poor posture / pelvic imbalance has not yet been documented. However, the available evidence with respect to anterior pelvic tilt, which is usually associated with individuals with spastic type cerebral palsy, indicates that this tilt arises as a result of biomechanical alterations occurring between

the skeletal muscles and bony components. To date the methods and clinical practices that underline the rehabilitation and restoration of normal posture following an anterior pelvic tilt, only appear to be anecdotal and therefore require scientific investigations.

2.5 Anatomy of the bony pelvis

The bony pelvis or pelvic girdle consists of three different bones (Figure 5): the sacrum in the midline posteriorly and one hip bone on either side (Cholewicki *et al*., 2000; Standring *et al*., 2005). In the anatomical position, the entire bony pelvis is orientated so that the anterior superior iliac spines and the pubic tubercle form a vertical plane (Cholewicki *et al.,* 2000; Standring *et al*., 2005). This arrangement enables the acetabulum to face laterally and inferiorly (Figures 6, 7 and 8), allowing the head of the femur a wide range of movements when fitting into the ball-and-socket joint (Bergmark, 1989; Hodges & Richardson, 1999; Cholewicki *et al*., 2000). The sacrum is an integral part of the pelvic girdle (Figure 6) and plays an important role in the functioning of the lower limb (Bergmark, 1989; Hodges & Richardson, 1998). Through the sacrum, the lower limbs are firmly fixed onto the axial skeleton, allowing rotation of the femur (and lower limb) on the bony pelvis more easily than would have been possible on an unstable pelvis (Damiano *et al*., 1995a; Hodges & Richardson, 1996; Cholewicki *et al*., 2001). Each hip bone has three major regions: the ilium, ischium and pubis (Bergmark, 1989; Moses, 2005; Standring *et al.*, 2005) (Figures 6, 7 and 8). The ilium is the superior part which gives attachment to the many abdominal and lower limb muscles (Tobias *et al*., 1988; Damiano *et al*., 1995a; Standring *et al*., 2005).

The ischium is the posterior segment of the hip bone with its prominent ischial tuberosity to which the hamstring muscles are attached (Figure 5) (Tobias *et al*., 1988; Damiano *et al*., 1995a; Standring *et al*., 2005).

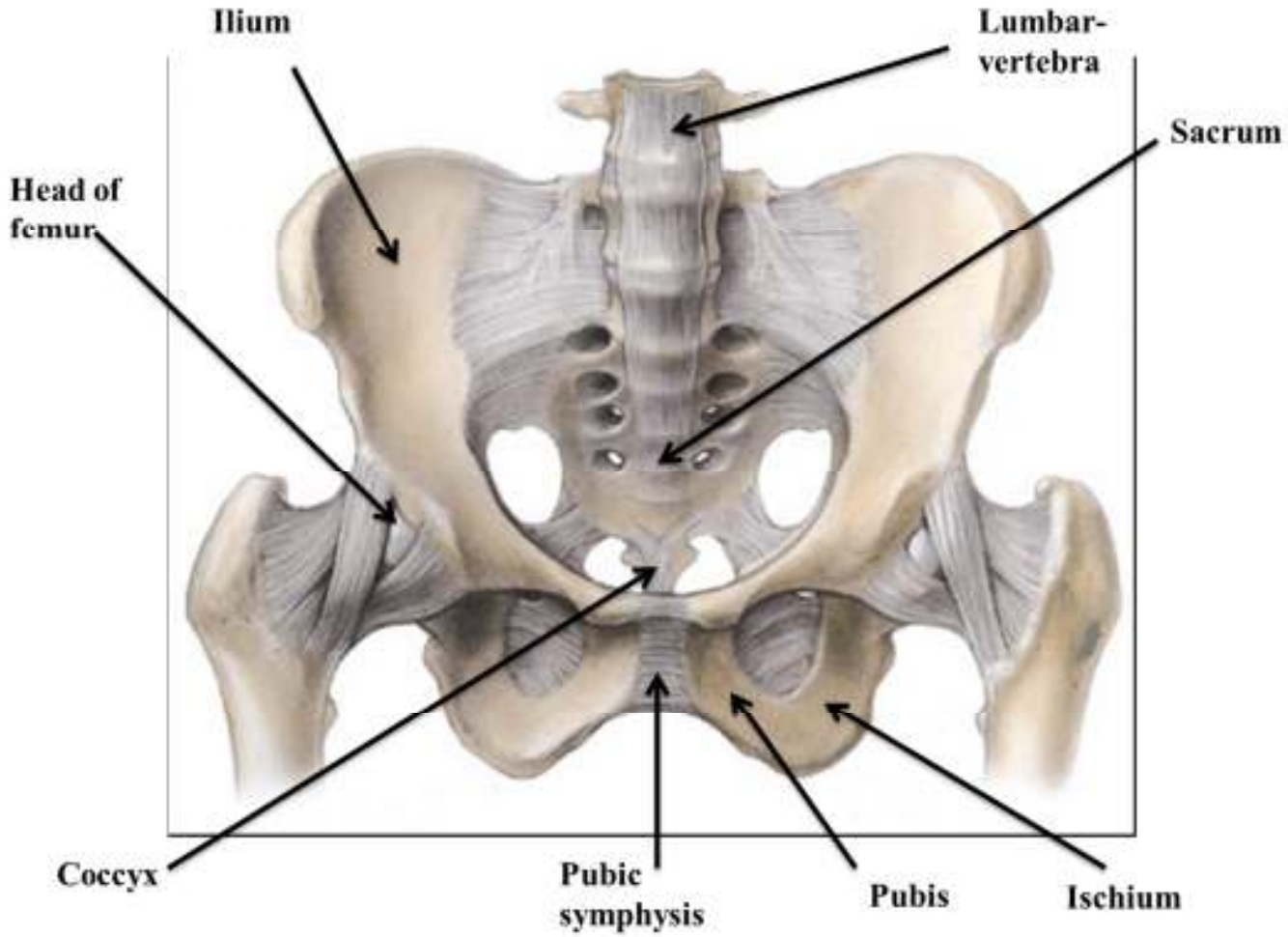


Figure 5: Diagram of the bony pelvis and its relationship with the hip joint. Adapted from: http://www.urogynecoly.co.il/im

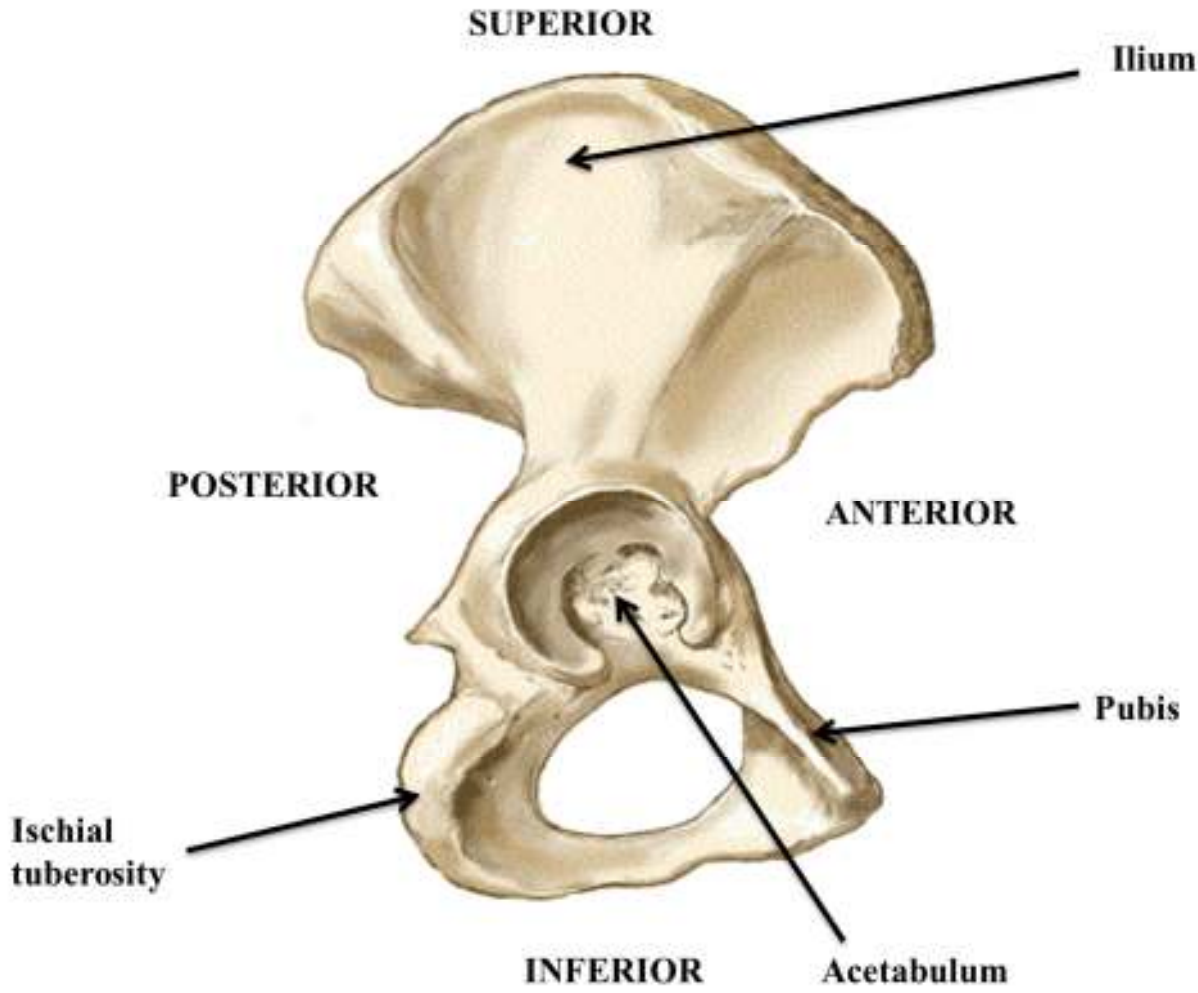


Figure 6: Lateral view of the right hip bone showing the ischial tuberosity
Adapted from http://fascstaff.gpc.edu/-jaliff/appendsk.htm 31 / 05 / 2013

The pubis is the antero-inferior segment of the bony pelvis (Figure 6) with superior and inferior pubic rami, uniting at the midline to form the pubic symphysis (Tobias *et al.,* 1988;

Through the pubic bone, all of the anterior abdominal muscles have their inferior attachments onto the bony pelvis and thus give a theoretical capability of mal-alignment in the event of any pathophysiology in either the anterior abdominal muscles or bony pelvis (Hodges & Richardson, 1996; 1999; Cholewicki *et al*., 2000).

2.6 Role of the abdominal muscles in maintaining trunk stability

Trunk stability is defined in this context as the ability to maintain equilibrium despite the presence of kinematic or control disturbances (Cholewicki *et al.,* 2000). It implies the ability to activate patterns of muscle co-ordination and posture to maintain balance, i.e. to keep the centre of gravity within the base of support (Hodges, 1999; McGill, 2002). Brogren *et al*. (1996) stated that, in reality anatomical or geometric anomalies are shown to be indicative of the potential for instability, with stability itself being an instantaneous phenomenon. Reports state that the trunk muscles mainly function to create torques which support postures and facilitate movements that ensure stability of the trunk and spine (McGill, 2002) and that stiffness is an important contributor to spinal stability and the maintenance of posture and balance (Cholewicki *et al.,* 2000).

Muscle stiffness increases with activation as a result of an increase in the number of activated cross-bridges (Stoylen *et al.,* 2000). Muscle activation has been shown to increase joint stiffness in the trunk (Vasseljen *et al.,* 2006) and it has been reported that with co-contraction, the activity of the agonist and antagonist muscles increases, thereby causing increased joint stiffness (Brogren *et al.,* 1996; Stoylen *et al*., 2000).

Bergmark (1989) proposed that the muscles controlling the trunk could be classified into groups. The first group includes muscles attached directly to the lumbar vertebrae that can provide spine segmental stability (Bergmark, 1989; Panjabi *et al*., 1992a; 1992b). The lumbar multifidus, transverse abdominal and internal abdominal oblique muscles are part of this group. These are also known as "local muscles" (Richardson *et al*., 2000). The second group consists of large torque producing muscles with no segmental attachment to the lumbar spine (Bergmark, 1989; Panjabi *et al*., 1992a; 1992b) and these are multi-segmental or "global muscles" (Richardson *et al*., 2000). These muscles include: the rectus abdominis, external abdominal oblique and thoracic erector spinae. The intersegmental muscles have been reported to function primarily as stabilisers while the multi-segmented ones function as moment producers (Bergmark, 1989; Panjabi *et al.,* 1992a; 1992b).

Although this distinction is well documented, there is still a debate among physical therapists over which muscle groups are important stabilisers of the trunk and how best to train the neuromuscular control system to ensure sufficient stability. However, an *in vivo* study by Cholewicki *et al*. (2000) showed that muscles that are antagonistic to the dominant moment of a particular task are the most effective at increasing stability. This observation therefore

suggests that the direction-dependent co-contraction pattern of the multi-segmented muscles to which the abdominal muscles belong may be useful trunk stabilisers and therefore worth investigating. This implies that abdominal musculature is heavily involved in controlling the trunk (Vasseljen *et al.,* 2009).

2.7 Role of abdominal muscles in maintaining pelvic stability

2.7.1 Lumbo-pelvic stability

As the trunk and upper body are balanced on the pelvis, the position of the pelvis may be key to posture and balance. There are a few researchers that have postulated that pelvic orientation is an important factor in the position of the lumbar spine (Richardson *et al*., 2002; Damiano *et al*., 2000). It has been shown that when the pelvis rotates or rocks posteriorly the lumbar spine loses the lordotic curve or may even become kyphotic (Richardson *et al*., 2000; Damiano *et al*., 2000). The greater instability of the pelvis during sitting compared with standing, led some researchers to suggest that, in the treatment of pelvic instability, the correct positioning of the 'pelvic belt' must possibly relate to the angle of pelvic rotation while standing (Panjabi *et al.,* 1992a; Hodges, 1999). It has also been proposed that relaxed postures rely on the passive lumbopelvic structures for the maintenance of an upright position against gravity with a diminished requirement of muscle activity. The continuous adoption of a relaxed posture is associated with motor dysfunction of spine-stabilising muscles such as the deep abdominal musculature (Snijders *et al.,* 1995). The transverse abdominal and internal oblique muscles have been reported to have a unique role in enhancing lumbo-pelvic stability, an action both muscles are able to perform via the thoracolumbar fascia (Hodges, 1999; Muramatsu *et al*., 2002. Additionally, the antero-inferior portions of the internal oblique and transversus abdominis muscles are capable of generating compression and hence increasing the stability of the sacroiliac joints (Snijders *et al.,* 1995; Richardson *et al*., 2002). Legerlotz and co-workers (2010) proposed that the pelvis shifts anteriorly to the thorax when an individual moves from erect to sway standing, and the centre of gravity comes to lie posterior to the bodies of the lumbar vertebra. The result of this is extension of the lower lumbar spine and lumbosacral junction (Panjabi *et al*., 1992b; Legerlotz *et al.,* 2010). Work by Barrett & Lichtwark (2010) indicated that maintenance of an upright position during sway standing is achieved mainly through activation of the anterior abdominal musculature.

2.7.2 Maintenance of the optimal pelvic tilt

With regard to trunk stability, the bony pelvis is likened to a see-saw positioned on the femurs (Damiano *et al*., 1994; Burtner *et al*., 1998; Woollacott *et al.*, 2005) and the muscles that attach to the bony pelvis have the ability to draw it anteriorly or posteriorly, influencing its rotation (Burtner *et al*., 1998; Hodges, 1999).

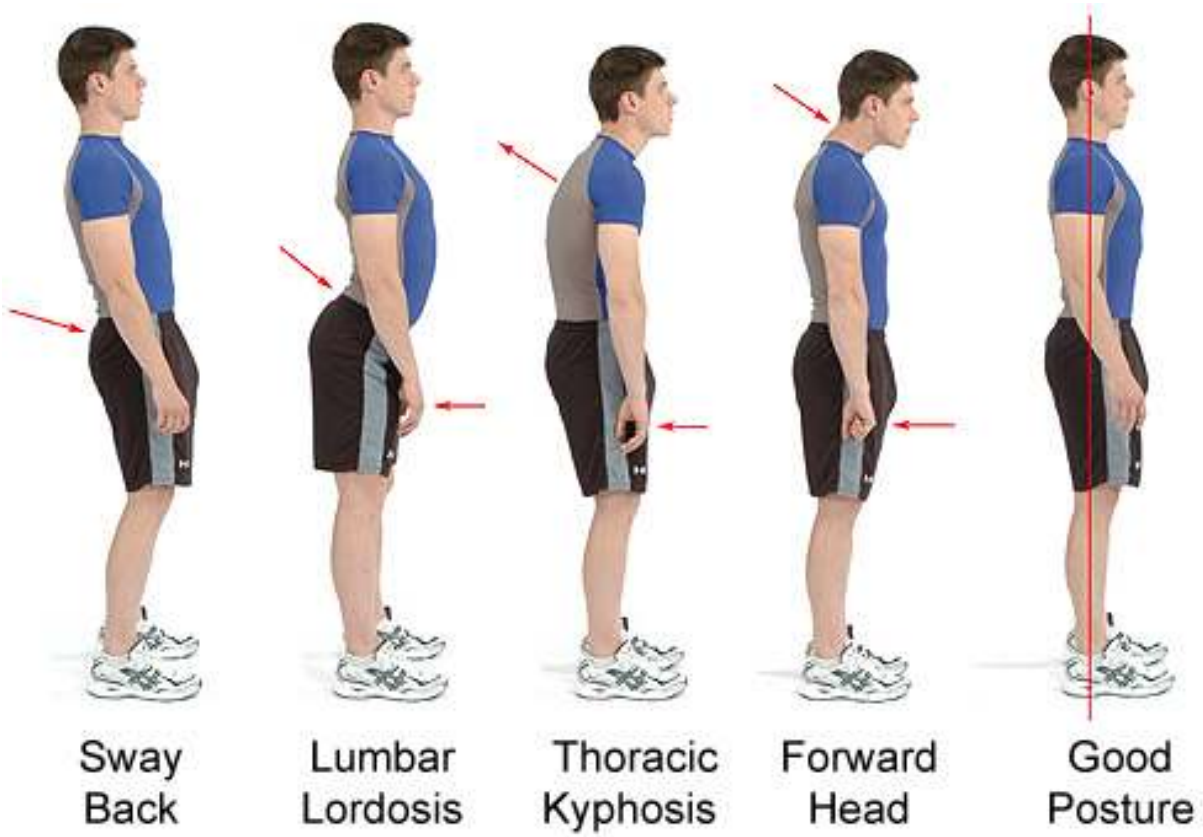


Figure 7: Pelvic tilt, lumabar lordosis and appearance of abdominal muscles in adults
Source: http://www.i.imgur.com/mtFaW.jpg

An anterior pelvic tilt is said to occur when the surrounding muscles (Figures 7 and 8) allow the pelvis to rotate forward (DeTroyer *et al*., 1990; Burtner *et al*., 1998; Hodges, 1999; Damiano *et al*., 2000). This may be observed when the anterior superior iliac spine of the bony pelvis is tipped anteriorly over the pubic bone in the coronal plane thereby creating a hyperlordosis (Hodges, 1999; Cholewicki *et al.,* 2000 –figure 8). The stability of the trunk and consequently the gait of an individual are affected when anterior pelvic tilt sets in as this accentuates the lumbar lordosis, moving the sacrum and coccyx markedly superiorly and posteriorly (Hodges, 1999; Cholewicki *et al.,* 2000; Vasseljen *et al*., 2009).

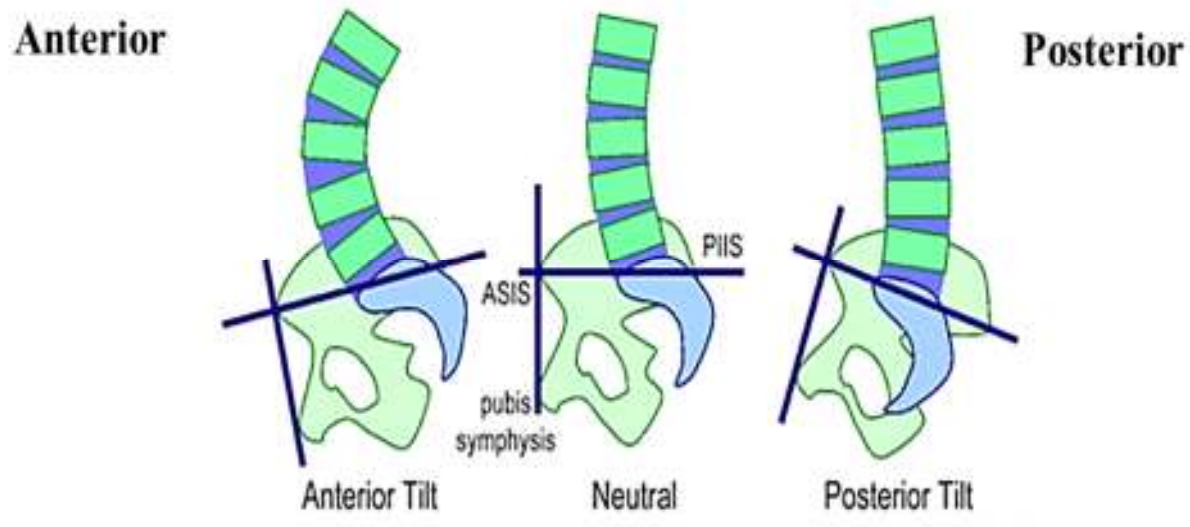


Figure 8: Diagram showing the positions of the bony pelvis
Source: http://www.floota.com/imag

From the anatomical and structural point of view, the pathophysiology of anterior pelvic tilt could be as a result of disturbances to any of the four main muscle groups which contribute to rotation and to a lesser extent the stability of the pelvis, Figures 8 and 9 (Cholewicki *et al*., 2000; Vasseljen *et al.,* 2009). These muscle groups include the abdominal and gluteal muscles, the hamstrings, and the hip flexors, Figures 8 and 9 (Tobias *et al*., 1988; Cholewicki *et al.*, 2000; Vasseljen *et al*., 2009). Weak gluteal muscles may allow the pelvis to rotate forward in the anatomical position (Damiano, 1993; Hodges & Richardson, 1999). The hamstrings are effective in stabilizing the pelvis posteriorly, therefore although not a probable primary cause of anterior pelvic tilt, weak and lengthened hamstrings can be a predisposing factor to an anterior pelvic tilt, especially when coupled with weak, inactive gluteal muscles (Hodges, 1999; Damiano *et al*., 2000; Vasseljen *et al.,* 2009). In addition, a tight lumbar erector spinae muscle group may play a role in anterior pelvic tilt as these muscles may produce an increased lumbar lordosis, which then increases the anterior force of rotation on the sacrum and therefore the pelvis (Hodges & Richardson, 1996; Hodges, 1999; Damiano *et al.,* 2000; Vasseljen *et al*., 2009).

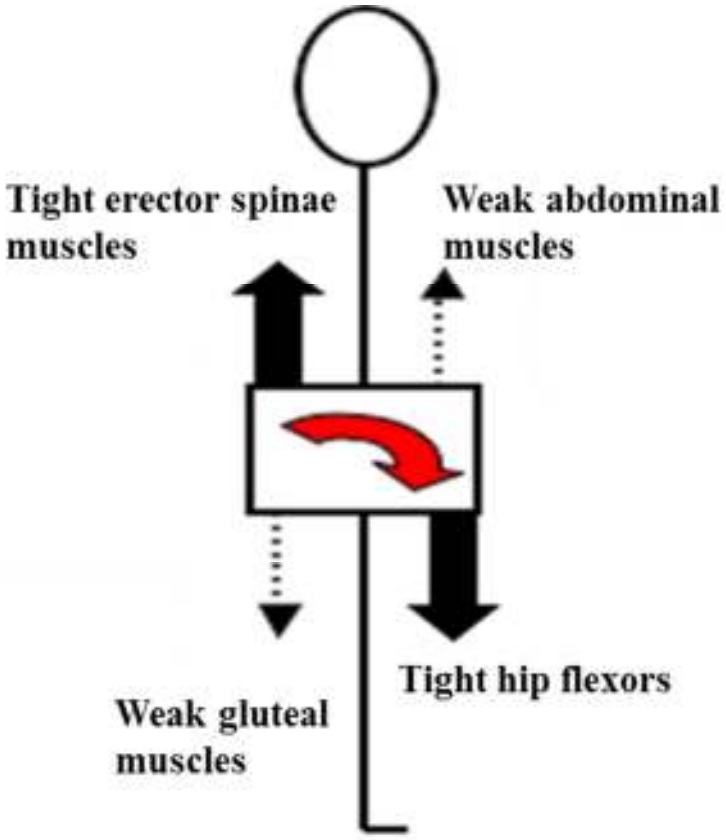


Figure 9: Diagram showing most probable factors in anterior pelvic tilt (red arrow) Adapted from: http://www.floota.com/imag

It has been reported that placing the thighs in a fixed position will allow the iliopsoas muscle to act as the principal flexor of the trunk and hip joints, and will also oppose the extension of the hip by the gluteal muscles (Hodges, 1999).

2.7.3 Influence of pelvic position on gait

In this context, the gait cycle which is defined as alternating movements of the two lower limbs resulting in forward thrust of the body is also easily compromised in bipedalism (Cresswell *et al*., 1992; Hodges & Richardson, 1999). According to Hodges (1999), this phenomenon of compromising the gait cycle in bipedalism could be by virtue of the attachment of the lower limb to the bony pelvis which is relatively unstable compared to quadrupeds. The process of evolution of mammals to bipedalism is noted to have impacted on three unique functions of the lower limb, namely the ability to bear body weight, provision of a means of locomotion and maintenance of equilibrium or stability of the trunk (Cresswell *et al.,* 1992; Hodges & Richardson, 1996; 1999). The lower limb is said to be adapted more for stability than for range of motion therefore, a condition such as anterior pelvic tilt, is

thought to affect the functioning of the lower limb and thus impacts negatively on the trunk muscles (Burtner *et al*., 1998; Hodges & Richardson, 1999; Damiano *et al.,* 2000).

A qualitative measure of gait cycle in bipedalism, may give an indirect evaluation of the cause of pelvic tilt (Damiano *et al.,* 2000). In bipedalism where the range of movement of the lower limb is determined by nature of the articulation of the femur with the bony pelvis, (i.e. the hip joint) an analysis of causes of anterior pelvic tilt should of necessity encompass the gait cycle and functions of the lower limb (Cresswell *et al*., 1992; Hodges & Richardson, 1999; Burtner *et al.,* 1998; Damiano *et al*., 2000). This is particularly important as movement of the lower limb at the hip joint usually involves the weight bearing bony pelvis moving on the femur and / or the non-weight bearing femur moving on the pelvis, Figure 9 (Burtner *et al*., 1998; Damiano *et al*., 2000). This mechanism of movements of the skeletal components of the bony pelvis, hip and lower limb is therefore considered to have a transforming effect on the attached muscles. As a result of dynamic interplay between articular parts and muscles, a disturbance in either of these movements is capable of bringing a reciprocal inhibition in action in any of the muscle groups attached to the bony pelvis and consequently tilting the bony pelvis (Damiano *et al*., 2000; Gage, 2004).

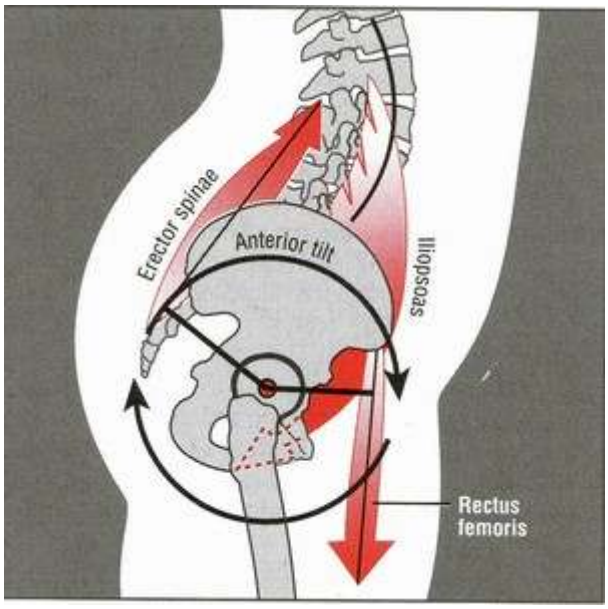


Figure 10: Diagram showing the bony pelvis and the attachments of other muscles with regard to anterior pelvic tilt
Adapted from: http: // www.musicstrong.com/anterior-pelvic-t

A transformation of the gross structure of the bony arrangement of the pelvis is perceived to have resultant changes on the ultrastructure of muscle groups attached to it (Shortland *et al.,* 2002). Ohata and co-workers (2008) noted that, regardless of which particular group of muscles is involved in anterior pelvic tilt, it is worthwhile exploring all parameters of a skeletal muscle responsible for full range of activity in order to understand the pathophysiology of one group or the other. This study seeks, among other objectives, to determine whether there are differences in trunk muscle activation between the STCP and TD groups and whether children with STCP and a reported anterior pelvic tilt are predisposed to poor activation patterns with respect to EMG analysis.

2.8 Conclusion regarding the role of the abdominal muscles

It can be seen from the above, that the muscles of the anterior abdominal wall are complex and that they play a vital role in the maintenance of the upright posture. The individual muscles of the abdominal wall have different functions with regard to supporting an upright posture, highlighting the fact that these muscles do not act as a homogenous group (Bergmark, 1989; Richardson *et al*., 2002; Gage, 2004). This is done through increasing the stiffness of the trunk through muscle activation and by maintaining the correct degree of pelvic tilt to allow optimal posture. The pelvic position is related to the ability to ambulate effectively and poor function of the pelvis by the abdominal muscles, amongst others, may well impact on gait efficiency (Deluca, 1991; Gage, 2004; Hodges *et al.,* 2005).

These muscles seem to be particularly susceptible to malfunction in different conditions such as low back pain in adults and cerebral palsy in children. (Hodges *et al*., 2006; Vasseljen *et al.,* 2009).

2.9 Cerebral palsy (CP) in relation to structural and functional body parts

CP is defined as a non-progressive lesion in the developing brain which typically affects a child's movement and postural tone (Palisano *et al*., 2000; Bax *et al*., 2005; Rosebaum *et al*., 2007). Therefore, CP may be regarded as a central nervous system condition with a motor impairment component affecting skeletal muscles (Morrel *et al.*, 2002). In 2001, the World Health Organisation developed the International Classification of Functioning Disability and Health (the ICF) in which disability was reconceptualised as arising out of the interaction between impairments of body structure and function, functional impacts which refer to activity limitation and / or social impacts which are linked to participation restrictions within

a contextual background (WHO, ICF, 2001). Impairments are defined as deficits within the structure or function of the body parts and include damage to a muscle (impairment of structure) or muscle weakness (impairment of function). In contrast, functional limitations refer to the inability to perform tasks such as walking or dressing oneself. Participation restrictions refer to an inability to play a social role. This framework has been used to discuss the disability associated with CP, both within the literature (Palisano *et al.*, 2000) and in this thesis.

2.9.1 Classification of CP

CP can be classified according to type, distribution and functional ability (Gorter *et al*., 2004). Researchers have documented three main types of CP with the spastic type (STCP) being the most common. This is characterised by hypertonia, hyperreflexia and constantly contracted tight muscles with stiff and difficult movements (Morrel *et al.,* 2002; Bax *et al.,* 2005; Rosebaum *et al.,* 2007). Consequently the acronym STCP will be used from this stage of the dissertation onward, to represent the very subtype that is being investigated in the present study. From the morphological perspective STCP may be regarded as an upper motor neurone lesion with severe consequences on various skeletal muscles, including the trunk muscles.

The other two types of CP, which are outside the scope of this study, are the athetoid type that is characterised by involuntary and uncontrollable movements and the ataxic type, characterised by a disturbed sense of balance and depth of perception (Chapman & Madison, 1988; Deluca, 1991; Deluca, 1996; Couper, 2002; Gage, 2004).

With regard to distribution, children can either present with the involvement of one limb (monoplegia), primarily the limbs and trunk on one side of the body (hemiplegia), involvement of primarily the lower limbs (diplegia) or all four limbs (quadriplegia) (Morrel *et al.,* 2002; Bax *et al.,* 2005).

The gross motor function classification system (GMFCS) Levels (Stanley 1989; Palisano *et al.,* 2000; Bax *et al*., 2005) serves to categorise the functional ability of children according to their ability to ambulate and has been found to have concurrent and predictive validity. According to Palisano *et al*. (2000) the grouping of individuals with STCP was based on self-initiated movements with particular emphasis on the control of the trunk. The primary criterion for the definition of the five levels of the disability classification system was based

on the distinctions between levels of motor functions (Palisano *et al*., 2000; Rosenbaum *et al.,* 2007). Other factors considered in this classification were based on the need for assistive devices and the degeree of quality of movement by individuals with STCP (Palisano *et al*., 2000). With this system of classification, Level I has been documented to include children with neuromotor impairments whose functional limitations are less than what is typically associated with cerebral palsy and diagnosed with minimal severity, while Level V includes individuals most severely affected with cerebral palsy (Palisano *et al*., 2000). Refer to Appendix B 2 for the interpretation of the five GMFCS classification Levels.

2.9.2 Impairments

Children with CP are reported to have various impairments that interfere with their activity and participation (Palisano *et al*., 2000; Ohata *et al.,* 2008). These impairments include neuromuscular and musculoskeletal problems such as spasticity or hypertonia and spasticiy, weakness, muscle contracture, lack of co-ordination and loss of selective motor control (Damiano, 1993; Burtner *et al*., 1998; Gormley, 2001). *Hypertonia* is noted to be present due to spasticity, which is a velocity dependent increase in tonic stretch reflexes, excessive co-activation of antagonist muscles and increased stiffness around joints (Deluca, 1991; Hagberg *et al.,* 2001). It is a common impairment in children with CP and the relation between higher resistance torque and lower strength is mainly determined by muscle morphology and neurological factors (Krageloh-Mann *et al*., 1993; Hagberg *et al.,* 2001). Only a weak to modest relationship between spasticity and function has been reported (Damiano *et al*., 2000; Ross & Engsberg, 2007).

Weakness or poor muscle activation has been documented as another major impairment and even children with mild CP have been shown to demonstrate substantial weakness compared with age-related peers (Damiano *et al.,* 2000; Barber *et al.,* 2011; Gough & Shortland, 2012). An increasing amount of research on CP in recent times, seeks to investigate the origin of the weakness and impairments. (Damiano *et al.,* 2000; Elder *et al*., 2003).

Spastic type cerebral palsy is closely linked to *trunk instability and poor balance*, either due to spasticity, weakness or other factors (Damiano *et al.,* 2000; Gough & Shortland, 2012). There are also reports of tightened psoas major muscles decreasing the range of motion at the hip joint, especially since the hip extensors (especially the gluteus maximus muscle) become reciprocally inhibited and unable to contract efficiently, therefore becoming a predisposing factor to anterior pelvic tilt (Hodges, 1999; Damiano *et al*., 2000; Vasseljen *et al.,* 2009).

The resulting unstable bony pelvis is capable of changing an individual's gait cycle as is common with STCP (Panjabi *et al*., 1992b) Altered gait cycle, can in turn, gradually transform the gross and ultrastructural design of the muscles involved in bringing about both stability and movement of the trunk (Chapman *et al.,* 2008; Tucker & Hodges, 2010). According to Chapman *et al.* (2008) the altered patterns of recruitment in trunk muscle fibres may have a possible relation with the histo-architecture of the muscles. The current study measured the sEMG activity in the abdominal muscles in order to relate muscle structure (weakness) to function.

2.10 Activity limitations

2.10.1 Gross motor function measure (GMFM)

The gross motor function measure (GMFM) is a criterion-referenced observational tool that was developed and validated to assess children with cerebral palsy (Russell *et al*., 2000; Rosenbaum *et al.,* 2002; Avery *et al.,* 2003). It has been reported that the reliance on personal experience can create a situation in which parents receive conflicting information on the progress of treatment of their children, hence the importance of a standardised motor function assessment tool such as the GMFM (Palisano *et al.,* 2000).

The GMFM is not designed to compare the function of children with cerebral palsy to typically developing children but can be used with any child or adolescent diagnosed with cerebral palsy (Avery *et al*., 2003). According to experts, this tool is meant to measure the gross motor functions in lying and rolling, crawling and kneeling, sitting, standing and walk-run-jump activities (Palisano *et al*, 2000; Russell *et al*., 2000; Rosenbaum *et al.,* 2002; Avery *et al.,* 2003). The inclusion of the GMFM in the current study is based on a variety of factors including problems with functioning associated with the different levels of STCP. The choice of this testing instrument is also based on reports that this outcome measure follows the extent of achievement of a variety of gross motor activities requiring postural control (Rosenbaum *et al.,* 2002; Avery *et al.,* 2003). Additionally, the GMFM test has been reported to use scores derived from a standardised score sheet, GMFM-66 or -88 as a measurement developed on the itemised scale (Rosenbaum *et al.,* 2002) that administration of the test has been made simple. However, some authors noted that professionals rely on personal experience in addressing the prognosis for the GMFM of an individual with STCP (Russell *et al*., 2000).

There has been mixed reports on the direct correlation between the GMFM scores and age, muscle strength as well as with anthropometric scores. According to Moreau *et al.* (2009) most fuctional activities of daily living such as walking do not require maximum strength, therefore the GMFM score may be an oversimplication of motor impairments of an individual. While age alone was reported to be a poor predictor of GMFM (Palisano *et al.,* 2000), some investigators also reported that a weak to modest relationship exist between spasticity and gross motor function and spasticity (Damiano *et al.,* 2000; Ross & Engsberg, 2007). Muscle strength especially in the quadriceps femoris, was reported to be highly correlated with GMFM (r = 0.70 to 0.83) (Damiano *et al.,* 2000; Ross & Engsberg, 2007; Goh *et al*., 2006).

The current study used this standardized tool (GMFM) to relate activity of the different abdominal muscles to function and age within the various disability levels.

2.11 The use of ultrasonography to produce images of MAP

As ultrasonography will be used to produce the images of MAP, this section describes the functional components of the equipment designed to produce visible images from biological structures. The principle is the conversion of electrical energy to sound energy and transcribing these sound energies from the different depths of the biologically scanned object into echoes (Hedrick, 2004). Echoes at different frequencies (time) are detected and then translated into 2D or 3D images (Hedrick, 2004; Szoab, 2004). This machine is therefore a useful tool for non-invasive scientific investigations.

Generally, an ultrasound scanning machine (US) has a transmitter, transducer (in the form of a hand-held probe) and a processor as its basic components (Sloan, 2004; Szoab, 2004). Contained in the probe are multiple acoustic transducers that send sound impulses into the material (Hedrick, 2004; Sloan, 2004; Szoab, 2004). The processor detects, amplifies back scattered wave (echo) and manipulates the reflected signals to form an image which can be recorded and stored (Sloan, 2004; Szoab, 2004). The transducers are made up of ceramic material (user & patient friendly) and are piezoelectric, producing short sound waves (Hedrick, 2004; Sloan, 2004; Szoab, 2004). The transducer is encased in a housing which may take variable forms (Hedrick, 2004; Sloan, 2004; Szoab, 2004). Strong but short electrical pulses from the US make the transducer ring at a desired frequency (Hedrick, 2004). Standard frequencies for biological structures in medical imaging range from 2 – 18Hz (Hedrick, 2004; Sloan, 2004; Szoab, 2004). Lower frequencies (2.25 – 5.5Hz) are used to

evaluate deeper structures from the surface (12 – 15cm) and higher frequencies (7.5 – 18Hz) penetrating within only 1 – 3cm from the surface of structures are used (Hedrick, 2004; Sloan, 2004; Szoab, 2004).

Whenever a sound wave encounters material with different density (called acoustical impedance) part of the sound wave is reflected back to the probe and detected as an echo (Hedrick, 2004; Sloan, 2004; Szoab, 2004). The sound produced is focused by either the shape of the transducer, a lens in front of the transducer or a complex set of control pulses from the US machine (Hedrick, 2004; Sloan, 2004; Szoab, 2004). This modern US machine (SIEMENS® ACUSONIC X150), being used for this study uses phased array techniques to change the direction and depth of focus (Hedrick, 2004). A rubber coating on the face of the transducer, acting as an impedance matching material, enables the sound wave to be transmitted efficiently (Hedrick, 2004; Sloan, 2004; Szoab, 2004). In addition to this coating, a water-based gel was placed between the skin of subjects and the probe.

Specifically, sound is reflected from anywhere where there are density changes in the object being scanned (Hedrick, 2004; Sloan, 2004; Szoab, 2004). A linear array of transducers simultaneously scanned through a plane of the object (in this case, the abdominal muscles) and this was viewed as a two-dimensional image on the screen. Thus B-mode was used to capture and store information from the muscles as "real-time". In some cases, where further clarity was required in this study, the A- and B-modes were manipulated to capture an image in the C-mode, viewing the muscles in their 3-D state.

With regard to safety concerns about this equipment, it has been reported to provide real-time interactions and lacks bio-effects (Hedrick, 2004; Sloan, 2004; Szoab, 2004). It is also generally considered to have no known or reported side effects (Hedrick, 2004). Careful selection of correct scanning parameters, namely mode, frequency and good practice ensured that optimum results were obtained.

2.12 Studies on MAP

The subsequent sections outline and appraise some studies done from other parts of the body using similar methodologies. The strengths and weakness of these documents have been critiqued with their relevance on the choice of instrumentation and design for this thesis. Each of these sections provides a guideline to the measurable objectives for the present study. Search results on studies involving MAP's and STCP yielded data mainly pertaining to either

the gastrocnemius or quadriceps femoris muscles. This is surprising in the light of the observed clinical practice in terms of physical rehabilitation of posture and balance in STCP cases where the trunk muscles, most often the abdominal muscles, are the target (Hodges & Richardson, 1996). Work by Shortland and colleagues (2002) is the first documented evidence in this area of research on STCP and MAP, which is reviewed briefly below.

Aside from its novelty, the study by Shortland *et al.,* (2002) fails to give a full explanation of the complex subject of cerebral palsy and muscle function / dysfunction. Despite the influx of studies on STCP, there is still a lack of understanding on the correlation between the basic MAP's of trunk muscles, the condition (STCP), the perceived deformities and the practice in the management of STCP. Therefore, this review of the literature is primarily focused on those studies that addressed critical morphological rather than studies aimed at exploring the broad perspective of the mechanical changes or deformities that are associated with cerebral palsy. However, the review process was not focused on the causes of these mechanical changes; whether they were as a result of CNS dysfunction or simply due to musculoskeletal alteration, but rather on the nature of the changes.

Researchers in the last two decades have attempted some form of investigation into the field of cerebral palsy and muscle architecture in order to fully understand the concept and the involvement of muscle thickness, muscle fibre length and pennation angle as being the principal components of MAP's that determine the capacity of a particular muscle to generate maximum force. Frequently, these researchers fail to measure empirically all three of these parameters in a particular muscle in their bid to evaluate muscle function / dysfunction as noted in the case of Binzoni and colleagues (2001) above. Other investigators, such as Ohata *et al.* (2008), also limited their hypothesis and evaluations only to muscle thickness while Shortland *et al*. (2002) measured only muscle fascicle length in TD children and those with spastic diplegia.

This section details studies on the use of ultrasonagraphy specifically to measure pennation angles and muscle thickness and muscle recruitment, utilizing similar tools to the current study in both typical developing children and adults and those with CP.

2.12.1 Cerebral palsy and ultrasonography

Researchers appear to be selective in their investigations of muscle architectural parameters (MAP) in an individual. There are few studies of high quality which fully address all three

components of MAP's (muscle thickness, muscle fibre length and pennation angle as being the principal components of MAP) in a single investigation. For instance, a classical study in this area by Binzoni *et al.* (2001) in typically developing subjects was only meant to validate the observation by Woittiez and co-workers (1984) that a large pennation angle allows for the production of greater mechanical force. Binzoni *et al*. (2001) started with the presupposition that muscle architecture is subject to a certain degree of plasticity and they were not investigating the transformations in muscle parts as a result of changes in MAP's due to a condition such as CP. However the context of their investigation (looking at pennation angle), the background of these investigators (a scientist, a sonographer and a pediatric orthopaedic surgeon) and their methodologies qualify their paper to be included in this review as one of the core or index literature that can guide the present study to obtaining credible results.

2.12.2 MAP's in typically developing children and adults

Recently, Legerlotz *et al.* (2010) conducted research on the suitability of ultrasound measurements of muscle architectural parameters (MAP) in healthy children. This team of researchers expressed concerns over the increasing use of different versions of ultrasound machine, in an ever changing technological era, to measure MAP's for clinical purposes. To this effect, some aspects of their investigation tested the *reliability* of measurements of MAP's of the medial gastrocnemius muscle in TD children using a stationary Philips HD 11 Real-Time ultrasound machine and a portable Chison 8300 Digital B-mode ultrasound machine. Legerlotz and co-workers (2010) showed in their results that the position of body parts (in their case the foot) produces varied results and thus brought a principal variable, known as orientation of body parts to the methodology of ultrasonography and measurement of MAP. Images taken with either brand of the ultrasound machine when the talocrural ankle joint was at the neutral position (90°) and at maximum plantar flexion showed significant difference. The mean MAP values of the medial gastrocnemius in these TD children at the neutral position as measured by the stationary ultrasound machine were as follows:

- Muscle thickness was 11.1 mm ± 1.4 mm,
- Pennation angle was 15.7° ± 1.8° and
- Muscle fibre length was 41.2 mm ± 6.2 mm (Legerlotz *et al.,* 2010).

The measurements obtained with the portable Chison 8300 Digital B-mode machine also fell fairly well within this range. However, the mean MAP values determined at maximum

plantar flexion position for the medial gastrocnemius were significantly different from measures determined with the ankle in a neutral position. Deep and superficial aponeuroses and fibre orientation within the medial gastrocnemius muscle were also shown to be identifiable in images obtained using either of the two ultrasound machines (Legerlotz *et al.,* 2010). Furthermore, their results after six weeks in a cohort of subjects justify the use of either a portable or stationary ultrasound machine for the determination of longitudinal changes in MAP's in young children with or without rehabilitation interventions.

Muscle thickness is one MAP's value that correlated significantly with age (r = 0.63) according to Legerlotz *et al.* (2010). *Pennation angle and muscle fibre length* were not significantly related to age (r = 0.26 – 0.32). Their data from the different legs of the same individual showed differences in MAP's with the use of both stationary and portable ultrasound machines at a neutral ankle joint position. According to these authors, muscle thickness varied from 1.1 mm ± 0.7 mm while the variation of pennation angle between the two legs of the same individual was 1.7° ± 1.3° and that for muscle fibre length was 4.8 mm ± 4.0 mm. These differences were, however, described as not statistically significant but as the subjects were all healthy children, this observation serves as another valid reason for the comparison of measurements between left and right sides in subjects who have spastic hemiplegia in the present study.

When compared to the present study three limitations could be identified in the work of Legerlotz and colleagues (2010), namely:

- limited only to healthy individuals
- small sample size, n = 21, and
- the measurements of MAP's were restricted to the medial gastrocnemius muscle only.

These limitations notwithstanding, their work still showed a strong reliability of MAP values when using either of the two brands of ultrasound machines, indicating the suitability of the use of ultrasound for the quantification of MAP. Furthermore, their results showed clearly that age correlated positively with muscle thickness values in the medial gastrocnemius muscle. Therefore their methodologies could safely be adopted in measuring some of the objectives of this study.

The aim of the study by Binzoni and co-workers (2001) was to determine whether some sort of adaptation, or a physiological or ancestral phylogenic change, may occur during human

growth. Their hypothesis was that the *pennation angle* for a newborn who has not yet used his / her legs for weight bearing and locomotion will be small. Consequently Binzoni *et al.* (2001) tested their hypothesis by investigating whether the pennation angle of the medial gastrocnemius increases during growth of the individual using ultrasonography. These researchers had a fairly large sample size, n = 162, widely distributed in age and therefore their results and conclusions are credible. Additionally, the methodologies used by Binzoni *et al.* (2001) are sufficiently comprehensible and repeatable in order to serve as a useful reference for the present study irrespective of the fact that subjects with CP were not specifically studied.

In contrast to the Legerlotz *et al.* (2010) study, Binzoni *et al.* (2001) found that pennation angle increases in the medial gastrocnemius monotonically from a mean of 2° at birth, attains a stable mean value of 22° at about twenty-years-of-age after which they noticed a steady decline to about 16° at about seventy-years-of-age. The results for muscle thickness also showed similar patterns, ranging from a mean of 3mm at birth, reaching stable mean value of 20 mm at about twenty-years-of-age before declining gradually to 12 mm at seventy-years-of-age. The current study however, recruited participants between the ages of seven- and sixteen-years-old for the in contrast to the age range of the the work of Binzoni and co-workers. These investigators concluded that pennation angle is not a constant parameter as a function of age but evolved as in the case of bone length and total body height. These observations and conclusions by Binzoni *et al*. (2001) are significant to one of the measurable objectives of the present study which is aimed at determining whether individuals with postural imbalances are capable of overcoming these conditions as they grow from childhood through adolescence to adulthood. With regards to the other two components of MAP, Binzoni and co-workers inferred from their results that muscle fibre length was simply a function of muscle thickness. The results of Binzoni *et al*. (2001) showed that males and females were statistically different with respect to MAP's but failed to comment on the significance of this, which was only illustrated graphically.

2.12.3 MAP's in children and adults with CP

In their work on adults with STCP and MAP, Ohata and co-workers (2008) stated that the muscle strength of people with severe cerebral palsy may be difficult to quantify because of cognitive and selective motor control problems. These investigators showed that if muscle strength is related to muscle atrophy caused by activity limitation, then quantitative

morphological analysis such as muscle thickness, measured by ultrasound imaging may be used to examine muscle condition in daily use (Ohata *et al*., 2008). Results from their work revealed that muscle thickness may be an alternative method of quantitative muscle evaluation for people with severe STCP for whom direct measurement of muscle strength is difficult (Ohata *et al*., 2008). Although these investigators clearly spelt out their null hypothesis that muscle strength is mainly determined by morphological and neurological factors, their data and conclusions were limited only to muscle thickness values as obtained from ultrasonographic measurements. The results from their study (Ohata *et al*., 2008) therefore, appear to equate muscle morphology with muscle thickness and thus fail to accurately represent the architecture of all skeletal muscles, including pennate and parallel muscle fibres. As mentioned earlier, the force-generating capacity of a skeletal muscle and consequently muscle strength is a composite parameter of the muscle architecture determined by pennation angle, fascicle length (muscle fibre length) and muscle thickness (Binzoni *et al*., 2001; Shortland *et al.,* 2002). In the present study, all three of these parameters will be measured with the use of ultrasound to determine their relationship with respect to muscle strength / activity.

According to Ohata and co-workers (2008) it is unclear whether muscle thickness is related to activity and participation as given by their GMFM values and measurements of quadriceps thickness obtained by ultrasonography. This observation, however, differs from what was stated earlier by Palisano *et al.* (1997) that muscle thickness in adults with STCP, as evaluated by ultrasound measurements, correlates with the severity of the condition (i.e. the GMFCS levels). These two teams of investigators on this aspect of STCP worked on different age categories, namely children and adolescents in the case of Ohata *et al.* (2008) as opposed to Palisano *et al.* (1997) who worked on adults. The results and conclusions from the work of Ohata and colleagues (2008) confirmed those of many other studies, in that ultrasound measurements in the B-mode is a reliable method of quantifying MAP's in individuals with STCP. Their results and conclusions showed that there is a direct correlation between muscle thickness of quadriceps femoris and the GMFM-66 values in children and adolescents with CP.

One study encountered in the literature that compares favourably with the present study in terms of contexts and measurable objectives is that of Mohagheghi *et al.* (2007). The main aim of their study was to examine whether there is any difference in MAP's of the medial gastrocnemius muscle in paretic and non-paretic individuals with spastic hemiplegic STCP.

As is the case of many of these researchers who are interested in the morphological aspect of STCP, Mohagheghi and colleagues also investigated the gastrocnemius muscle and not the trunk or abdominal muscles. The inclusion of spastic cerebral palsy subjects and the protocols used to obtain their results qualifies the study of Mohagheghi *et al.* (2007) to be relevant to pursuing the research questions of the current study, irrespective of their small sample size of eight. Their inclusion criteria being STCP subjects with a mean age of about ten-years-old and their exclusion criteria such as botulinum toxin injection, surgical intervention in less than six months of the study and casts informed the study design of the present investigation in the abdominal muscles. The work of Mohagheghi and co-workers also categorised the subjects into GMFCS levels since they were interested in relating MAP's to disability levels of these subjects, an objective which is being measured by the present study. With regards to ultrasound technique, Mohagheghi *et al.* (2007) used a stationary ALOKA SSD-5000 system in B-mode real-time (made in Japan) while the present study also uses a stationary ACUSONIC X150 system B-mode in real-time (made in Japan).

According to Mohagheghi *et al.* (2007) two hypotheses motivated their investigation namely:

- the fascicle length of gastrocnemius muscle in the paretic leg of hemiplegic subjects would be shorter than the non-paretic leg, and
- muscles in the paretic leg would have undergone atrophy and a reduction in pennation angle compared to the non-paretic leg.

Their procedure follows a rationale that all fascicles identifiable throughout the whole lengths of the scan were selected for measurements as muscle fibre length. Similarly these investigators defined pennation angle as the angle formed between identified fascicles and the deep aponeurosis and muscle thickness in each of their scans as the perpendicular distance between superficial and deep aponeuroses. From the results shown by Mohagheghi *et al.* (2007) the muscle architectural parameter (MAP) in a particular section was taken as the mean of the measured parameters. The reliability of their results was appropriately documented as a same investigator repetition of 60% of randomly chosen subjects which yielded a high intra-class correlation co-efficient for each parameter ($r = 0.8$). Notable among the results were that there was no statistical difference in pennation angle in paretic and non-paretic legs, 18° and 19° respectively. The values of the pennation angle from their results did not agree with their hypothesis – it showed similarities in the paretic and non-paretic legs. In

terms of percentage, Mohagheghi *et al.* (2007) showed that muscle thickness in the medial gastrocnemius muscle reduced by 10% in paretic as compared to non-paretic legs.

Mohagheghi *et al.* (2007) concluded that spastic hemiplegic CP subjects had shorter fascicles, reduced muscle thickness and similar pennation angles compared with the non-paretic leg. Furthermore, they stated that muscle fibres may adapt to motor disabilities caused by brain injury by losing sarcomeres and thus by inference, a lower muscle thickness value may correlate to a higher GMFCS ratings, i.e. a poorer level of functioning. More important to this study despite their small sample size and lack of control subjects, is the conclusion that calls for further investigations to establish whether there is a relation between MAP and conventional indexes of disability in STCP before and after treatment. It is based on some of these studies and their conclusions that the present study is appropriately designed.

The above results are similar to those of Shortland *et al.* (2002) whose hypothesis was that muscle fascicle length is reduced in children with spastic diplegia, clearly set their aim to compare MAP of gastrocnemius muscle in TD and with children with STCP. They had a total sample size of sixteen, which is rather limited. Shortland and co-workers (2002) produced excellent data to show that muscle fibre length in the medial gastrocnemius muscle in TD children and children with diplegic STCP does not differ significantly. Owing to the fact that these investigators failed to detect a significant difference in fascicle length between these two groups at all the positions of the ankle joint, they thus rejected the null hypothesis. The conclusion by Shortland *et al.* (2002) was that a reduction in muscle fibre length does not account for the fixed shortening of the medial gastrocnemius muscle in ambulant children with spastic diplegia. Clinical observations reveal that the medial gastrocnemius muscle bellies in these children are short. This discrepancy therefore, points to the fact that only a meticulous measurement of all the components of MAP may help in providing a clear understanding on this subject. The present study looks at some of the shortfalls in the designs associated with these early studies and attempts to overcome them by the inclusion of large sample size (N = 145) and also by quantifying all three components of the MAP of the abdominal muscles.

Available information from the literature suggests that exercise and resistance training are important components of rehabilitation programmes for counteracting impairments at the muscle level in children and adolescents with STCP in order to improve the force of muscle output and efficiency (Damiano, 2006; Dodd *et al*., 2003; Vershuren *et al*., 2007).

According to Moreau *et al.* (2010) little is known about the mechanisms underlying these impairments and consequently undertook a morphological study on a selected group of antigravity muscles in children and adolescents, with or without STCP, to establish the anatomical and physiological basis of such a practice. Moreau *et al.* (2010) stated that the motivation for their study was that, although MAP is known to determine the force-velocity properties of the muscle as well as outcome measures of MAP being of clinical importance, there was no available data to prove this knowledge. To them, the differences in MAP in children and adolescents with STCP and those with TD were poorly understood and information about how MAP predicts muscle function in STCP was scarce in the literature. Even more scarce are studies reporting on how MAP predicts other impairments or GMFCS levels in CP, which are important for informing clinical practice. Moreau e*t al.* (2010) were of the opinion that based on their previous unpublished data it is possible that MAP is altered in these antigravity muscles in people with STCP due to disuse and low activity levels. According to these investigators the primary weakness and secondary disuse of the quadriceps muscle coupled with abnormal movement patterns may lead to muscle atrophy and re-arrangement of the internal architecture of a muscle and thus adversely affecting function (Moreau *et al.,* 2010).

One of the hypotheses of Moreau *et al.* (2010) was that muscle architectural parameter (MAP) is predictive of muscle function in children with CP. This was based on their previous work in typically developing (TD) individuals from which they concluded that MAP determines the capacity of force generation in a muscle. Their second hypothesis was that the anatomical and physiological relationships of muscle thickness and the maximum voluntary torque of the knee extensor muscle are similar in participants with or without STCP. The overall purpose of the study undertaken by Moreau and colleagues was to investigate the critical relationships between MAP and muscle function and the relationship between MAP and activity. In view of this, Moreau and colleagues (2010) set their primary objective at developing a predictive regression model of maximum voluntary knee extensor torque in children and adolescents with or without STCP on the basis of measurements of thickness of the rectus femoris and vastus lateralis muscles as obtained from 2D ultrasound imaging. That is to determine whether MAP of rectus femoris and vastus lateralis correlates to force generation in individuals with or without STCP. They also aimed at quantifying the relationships between MAP and the measures of activity and participation in individuals with STCP.

A sample size of thirty individuals, of whom eighteen were from the STCP group with a mean age of twelve years, and twelve typically developing children and adolescents with a mean age of twelve-years and four-months was used. Sample size was rather small for an investigation such as this. In the present study a larger sample size (N = 145) was used. The participants with STCP were from GMFCS Levels I – IV similar to the functional levels of the current study. The brightness mode (B-mode), two-dimensional ultrasound imaging procedure was followed, using a VOLUSON 730 EXPERT machine (stationary) with a 6 – 12MHz linear array transducer to determine measurements for muscle thickness, fascicle length and fascicle angle of both rectus femoris and vastus lateralis.

In relating MAP to muscle function and activity in participants with CP, Moreau and co-workers used Pediatric Outcome Data Collection Instrument (PODCI) and the Activities Scale for Kids, Performance version (ASKp). From their results, when age and GMFCS level were controlled for vastus lateralis muscle, thickness was the best predictor of the knee extensor torque in the group with CP ($R^2 = 0.85$). Moreau *et al*. (2010) also showed that rectus femoris muscle fascicle length was significantly correlated with the PODCI (p = 049) and vastus lateralis muscle fascicle angle was correlated with the PODCI (r = 0.47) and with ASKp (r = 0.50). These investigators thus concluded that:

- Ultrasound measure of vastus lateralis muscle thickness, adjusted for age and GMFCS Level, were highly predictive of maximum torque and
- Muscle thickness measure of ultrasound has the potential to serve as a surrogate measure of the ability to generate force in children and adolescents with or without STCP.

The relationships between all the components of muscle architecture (MAP) and muscle function are far from being understood, for instance considering pennation angle alone, even though the underlying rationale is that a larger angle of pennation allows more fibres to be packed within a given space no two studies as reviewed so far have yielded the same conclusion to match this principle. The work of Moreau and colleagues (2010) appears to fall short of the observation of decreased pennation angle in their STCP participants in their study with regards to activity and force generation. To them, the decreased pennation angles in the STCP group was as a result of or consequence of lower levels of mobility and locomotion.

A good study such as this, presenting with variations in results and conclusion, is an indication of the consequences of studying only one component of MAP. The current study explored all the parameters associated with the generation of muscle force.

2.13 Recruitment of muscle fibres and the use of EMG

Electromyography (EMG) is a technique to record and evaluate electrical activity produced by skeletal muscles (Nudo, 2003; Hlustik *et al*., 2004; Winchester et al., 2005), measured using an electromyograph that produces an electromyogram (Nudo, 2003; Wakeling *et al*., 2007). Physiologically, the electrical activity is considered to be the recruitment of muscle fibres (motor units or motor end-plates) (Wu *et al*., 2007). The motor unit is regarded as one motor neurone and all the muscle fibres it innervates (Nudo, 2003; Wu *et al*., 2007; Prosser *et al*., 2010). An EMG will reflect the degree of contractile response in a particular muscle when stimulated (Wakeling *et al*., 2007; Prosser *et al*., 2010). This instrument usually measures the membrane potential in muscle fibres and analyses the signals receive in various forms, i.e activation levels and order of recruitment (Wakeling *et al*., 2007; Prosser *et al*., 2010). In addition to other uses of EMG analysis, it has been reported that this forms a critical component in the examination of gait in individuals with STCP (Prosser *et al.,* 2010).

The analysis of the amplitude of EMG signals has been reported as a common method in research and clinical practice of recording muscular activity (Nudo, 2003; Winchester *et al*., 2005; Rosenbaum *et al.,* 2007) but this has been documented to be influenced by factors such as anthropometrics, precise electrode placement and overlying tissues in the body (Vasseljen *et al*., 2009; Prosser *et al*., 2010). The analysis of EMG amplitude in millivolts units is also reported to be useful in reflecting activity in a single muscle or group of muscles, whereas the evaluation of frequency in hertz units is the preferred choice for the comparing multiple muscles across individuals (Prosser *et al*., 2010). In the current study the activities of all four abdominal muscles are compared amongst each another in every participant for both of the groups, therefore the analysis of EMG activity by frequency was used.

Theoretically, normal muscle tissue registers no EMG activity at rest and during passive movement (Roncesclave *et al*., 2001; Rose & McGill, 2005; Lauer *et al*., 2007b). However, in practice the anti-gravity and postural muscles normally indicate a low EMG at rest since the motor action potentials do appear (Roncesclave *et al*., 2001; Winchester *et al*., 2005). Motor activity in muscles is responsive to commands generated in the central nervous system

and transmitted along the alpha motor neurones to the periphery (Roncesclave *et al*., 2001). The electrodes of the sEMG detect all the sums of muscle action potentials within a designated area (Ross & Ensberg, 2007). These signals represent the relative level of recruitment of a collection of motor units that underlie the electrodes (Roncesclave *et al*., 2001; Ross & Ensberg, 2007).

A motor unit consists of a single motor neurone and all the muscle fibres that are supplied by its axon (Roncesclave *et al*., 2001). The recruitment of muscle fibres occurs through individual motor units rather than individual muscle fibres (Roncesclave *et al*., 2001). When a motor unit is stimulated, all of the muscle fibres in the motor unit respond by attempting to shorten (all-or-none principle) (Roncesclave *et al*., 2001). The size of the motor unit influences the precision and force of movement (Roncesclave *et al*., 2001; Wakeling *et al*., 2007). One can thus ask the question as to whether the "all-or-none principle" could be the cause of weak abdominal muscles in STCP. The small ratio of muscle fibres to the motor unit results in the capability of producing more precise movement (Lauer *et al*., 2007a). When output of a large force is required from a muscle, more motor units are recruited within the muscle and as the force that is needed drops, the number of motor units that are activated decreases as well (Roncesclave *et al*., 2001; Lauer *et al*., 2007a).

There are reports that using frequency analysis of EMG signals can effectively overcome the potential problem of non-stationarity of the EMG signal usually associated with the analysis in the amplitude domain (Frigo & Crenna, 2009). The time-frequency characteristics of the EMG signal have also been shown to be elevated in leg muscles and to correlate with functional measures in individuals with STCP (Lauer *et al*., 2007b; Wakeling *et al*., 2007). Additionally, the EMG characteristics were reported to be sensitive to changes in muscle function after surgical intervention in individuals with STCP (Lauer *et al*., 2007; Prosser *et al.,* 2010). Finally, reports that the use of EMG frequency analysis does not require participants to generate a maximal force for the detection of signals (Vasseljen *et al*., 2009; Prosser *et al*., 2010) have made this analysis more attractive and useful in the current study than the conventional EMG amplitude analysis.

2.13.1 Studies on EMG and muscle activitiy

The use of the intramuscular EMG to determine the onset of muscle activity is the superior method, however this is limited by its invasive nature. Vasseljen *et al.,* (2009) investigated muscle activity in a different dimension by exploring how comparable the EMG activity of

abdominal muscles is with the use of the motion-mode (M-mode) US imaging to detect changes in tissue velocity. The present study is comparable to the work of Vasseljen and co-workers and some further studies are available on the EMG activity of the abdominal muscles, all of which are worth reviewing.

The aim and therefore methodology of the study by Vasseljen *et al.* (2009) were somewhat different from the current study. These authors were interested in measuring the rate of tissue strain in muscles and therefore the time taken for the visualisation of tissue in motion was the index quantified. Their study involved using an imaging technique to record tissue velocity (Kremkau, 2002) which they then related to changes in thickness and extrapolated to mean muscle activity. The current study focused on the frequency of activity in relating one group of muscles in an individual to another and also among individuals (D'hooge *et al*., 2000; Stoylen *et al.,* 2000).

The use of the M-mode US to detect EMG activity in muscles is done by observing the changes in muscle thickness using high temporal resolution images (Kremkau, 2002; Vasseljen *et al.,* 2006). This measured the tissue deformation gradient, processed and expressed it as tissue strain with the strain rates determined (Kremkau, 2002; Vasseljen *et al.,* 2006; Vasseljen *et al.,* 2009). The strain rates are considered as the time taken for the changes in thickness on contraction. Consequently, the results from such a method are compared with the EMG activity as measured simultaneously (Vasseljen *et al.,* 2009). In order to synchronise US and EMG readings, the time of onset of activity was the prime focus with the ultrasound probes being orientated superficial to the direction of insertion of the fine wire in the muscle fibres (Vasseljen *et al.,* 2009).

The result of the study of Vasseljen *et al.* (2009) showed that there was no consistent relation between changes in thickness and EMG activity in the IO and TrA, which were the only muscles that they studied. Their study concluded that ultrasound M-mode is a reliable alternative to measuring the onset of muscle activity in the abdominal muscles (Vasseljen *et al.,* 2009).

Studies by Prosser *et al*. (2010) compared favourably to some extent with the current study. These researchers investigated the use of EMG frequency analysis to compare the activation pattern of trunk and hip muscles in children with CP (N = 15) and TD individuals (N = 16). A 16-channel sEMG recording system was used by Prosser and co-workers to collect data from the rectus abdominis (RA) and external oblique (EO) and the posterior trunk and hip muscles

(Prosser *et al.,* 2010). The sEMG signals were detected from the activities of the muscles perceived by these investigators to be associated with posture during walking (Prosser *et al*., 2010). According to the methodology used by these researchers, it could be inferred that the RA and EO are the only anterior trunk muscles considered to be involved in the maintenance of trunk stability as opposed to the current study which includes all four abdominal muscles. Monitoring the gait cycle was an important aspect of their investigation since walking was the source of force generation for the muscles perceived to be attached to the pelvis (Prosser *et al*., 2010). A video monitoring device was included in their instrumentation to sychronise sEMG readings and gait (Prosser *et al*., 2010). Voluntary limb movement in the supine position served as a source of muscle activity in the current study. No video equipment was employed in the present study to monitor movement of body parts.

The results of Prosser *et al*. (2010) showed that higher EMG activity at the beginning of the gait cycle characterised all the postural muscles in the STCP than was recorded in children with TD. They suggested that the high mean EMG frequency in the STCP group during the stance phase was an indication of altered pattern of muscle activation (Prosser *et al*., 2010). According to Prosser *et al*. (2010) the higher mean EMG frequency observed in children with STCP could be attributed to muscle fatigue but was not necessarily an indication of the generation of force.

2.13.2 The functional outcome measures: gross motor function measure (GMFM) and physiological cost index (PCI)

A study by Bartlett *et al.* (2010) correlated the GMFM scores in adolescents with age among the three most severely affected STCP levels (Levels III to V). The sample size of 145 in the current study compares favourably with the investigation of Bartlett and colleagues who studied 135 adolescents with several palsy. However, Bartlett and co-workers recruited individuals between fourteen- and eighteen-years-of-age whereas in the current study participants ranged from seven- to sixteen-years-of-age.

Although the aim of the investigation by Bartlett *et al*. (2010) was somewhat different from the current study, there was adequate guidelines on the use of the GMFM tool for the current study as this was one of the few available reports that correlated GMFM scores with the anthropometric and demographic results of individuals with STCP.

The notable observations from the study of Bartlett and co-workers were that:

- Obesity was strongly associated with GMFM scores,
- GMFM scores discriminated strongly amongst disability levels, and
- The potential determinants of change in motor capacity were posture and anthropometric characteristics.

According to Bartlett *et al*. (2010) the peak of GMFM capacity in severly impaired individuals was between the ages of seven- and eight-years-old with a significant declines of about 4 to 8 GMFM-66 points as severely affected STCP individuals grow older.

It is anticipiated that the use of the GMFM testing instrument in the current study would provide useful insight ino the overall involvement of the abdominal muscle on posture amongst the various disability levels (GMFCS Levels). It is noteworthy that the inclusion of GMFM test in the present study is based on the hypothesis that this may serve as an indirect outcome measure in relating abdominal muscle structure (posture) to function.

Rosenbaum *et al*. (2002) studied children between the ages of one- and thirteen-years to report on the reliability of the GMFM as an outcome measure.

The physiological cost index (PCI) is a measure of energy expenditure during gait, and frequently used as an indicator of locomotor efficiency (Thomas *et al*., 1996). The higher the PCI, the more inefficient the gait pattern. The theoretical basis for PCI is the relation that is reported to exist between heart rate and oxygen uptake in healthy individuals up to submaximal workload (Nene & Jennings, 1992). In the present study, the inclusion of PCI test as an outcome measure in relation to MAP is based on the following assumptions:

- That abdominal muscles have poor recruitment patterns,
- That these poor recruitment patterns result in an to imbalance occurring at the trunk / bony pelvis,
- That this imbalance transforms the gait and cadence of individuals with STCP negatively, and
- That a transformed gait and cadence leads to high demands of energy in the form of oxygen consumption during locomotion.

This outcome measure is being tested based on the null hypothesis that there is no association between PCI and MAP in children with STCP.

Supportive evidence from the work of Nene *et al.* (1993), that oxygen uptake and heart rate are linearly related at submaximal levels with the possibility of an association between both tests with a PCI measure was one of the earliest investigations involving the use of PCI in individuals with motor impairments. Subsequently reports by Thomas *et al.* (1996) which indicate that a major contributor to poor walking ability of children is the poor control of balance also affirm the use of PCI in the investigation of gross motor function in individuals with cerebral palsy. As a result of the convenience of its use, PCI as an outcome measure for the assessment of gross motor function has been widely used and preferred to other tools. The According to Thomas *et al*. (1996) the use of PCI in the assessment of various gait abnormalities provides new dimensions to the success of treatment plans for the rehabilitation of STCP individuals. The estimation of energy expenditure in children with cerebral palsy using PCI as an evaluation tool was also documented by Rose *et al.* (1985). Despite the seemingly wide use of PCI, some authors such as Ijzerman & Nene, (2002) strongly argued that the most preferred method of determining energy expenditure by walking is the assessment of direct oxygen uptake. However, due to the inconvenience in the administration of the direct oxygen uptake method, studies by McCroy *et al.* (1997) provided sufficient evidence on the high association between the measure of oxygen uptake and the use of PCI in support of the use of PCI as a preferred alternative. The use of PCI is best regarded as requiring low and intermediate technologies and also user-friendly (McCroy *et al.,* 1997; Eston *et al.,* 1998).

A study with regard to the reproducibility of PCI and the oxygen uptake tests in children with CP showed that the oxygen uptake method was more reproducible (with an average of 13.2%) than PCI (average of 20.3%) (Bowen *et al.,*1998). However, reports by Nene *et al*. (1993) on adolescents and adults showed that PCI is a reproducible measure. The reliability of the PCI and oxygen uptake tests have also been studied by Ijzerman *et al.* (1999) who concluded that PCI was less reliable than the criterion standard test, which is oxygen uptake.

While the work of Nene (1993) showed that PCI scores could be a reliable measure of muscle activity in adolescents and adults, similar studies by Mossberg (2003) indicated that there was no direct evidence of a correlation between PCI and muscle activity. Recently, investigators such as Moreau and co-workers reported that PODCI and ASK_p were better outcome measures in predicting the strength of quadriceps femoris than the use of PCI as an outcome measure (Moreau *et al.,* 2013). Co-contraction, as determined by EMG activity in the quadriceps femoris, was reported to be inversely proportional to PCI (Damiano *et al.,* 2000).

Some of these latter studies support the choice of inclusion of the use of PCI as an outcome measure in the present study to determine whether a correlation exist between the trunk (abdominal) muscles and PCI scores.

In the current study the inclusion of PCI test is strongly motivated by its user-friendly technology and administration.

2.14 Summary

From the above review, there is evidence that the role of the abdominal muscles with regard to the positioning of the trunk is complex. Little is known about the histo-architecture or MAP's and the overall influence of these MAP's on the functioning of the abdominal muscles. The effect of STCP and the commonly associated weakness of the abdominal muscle has been given little anatomical and physiological consideration. However, the alterations in MAP components such as muscle thickness, fibre length and pennation angle of these thin group of muscles need to be fully understood in order to relate basic architecture of the abdominal muscles to the overall gross motor functions of individuals with CP. Since the use of US and EMG in the measurement of muscle structure and function respectively, has been documented to be reliable (Ferreira *et al*., 2004; Urquhart *et al*., 2005), the current study used these instruments as the main investigating tools of evaluating and relating muscle structure to function.

The bulk of the discussion in this chapter was on reviews of some of the relevant studies in the field of cerebral palsy with respect to transformation of body structures and how these studies inform the choice of methodologies used in the current research. This chapter also looked at the subject of cerebral palsy from an anatomical point of view. A description of the bony pelvis with respect to trunk stability and maintenance of posture was touched while the ultrastructure of skeletal muscles, with emphasis on those parameters that confer strength and maximum force to skeletal muscles in general, were discussed in detail. The hypothesis for this study and the broad views of some relevant researchers in the literature were also briefly addressed. The chapter highlighted the measurable objectives of the present study and explained the anatomical basis of the methods used. Finally, this chapter drew attention to the existence of a chasm between theories and practices on this subject, hence the importance of this study. The next chapter looks at the description of the subjects, instruments, materials and the methods used for this study.

Chapter 3 Materials and Methods

3.1 Study design and hypotheses

The study design is descriptive, analytical and cross-sectional. It is a descriptive study due to the fact that the data obtained by observation of the subjects were presented and discussed, analytical because variations of MAP's with respect to the different levels of STCP were examined, and cross-sectional because data were gathered from the children only once.

Note: Whenever the phrase *at rest* or *resting stage* is used in this study, it implies that the patient is resting and the muscle is *not* being used for active movement, even though the muscle at rest will have normal / raised / reduced tone.

3.2 Participants

The study population included a group of children with spastic type cerebral palsy (STCP) attending special or mixed schools in Cape Town and another group of typically developing (TD) children attending either mixed or open schools. A cluster sample of convenience was identified by recruiting children with STCP from children attending three local schools for learners with special needs. Children from the TD group were recruited from two public co-educational schools within the locality of the special need schools as well as from one of the special need schools that provides tuition for a mixed population of learners (CP and TD).

3.2.1 Inclusion / Exclusion criteria

According to Altman *et al.* (2001), inclusion (eligibility) criteria should be explicitly defined especially when using human subjects and the population of study should be restricted using selection criteria. This report also stated that eligibility criteria do not affect internal validity but do affect the external validity, and as such a careful description of participants and settings as shown below needs to be done so as to assess the external validity of this study.

3.2.2 Inclusion and exclusion criteria for TD children and adolescents

Participants fulfilled the following inclusion criteria:

- both participants and parents endorsed the consent / assent forms indicating their willingness to take part in the study,
- children aged between seven and sixteen-years-old, and

- children able to speak and understand English for easy communication between pupils and the principal investigator, who was unable to speak Afrikaans or isiXhosa, two of the local languages.

Exclusion criteria were:

- children suffering from any neurological condition as reported by their teachers or as evidenced by presentation of a medical report, and
- children having undergone any surgical operation involving the anterior abdominal wall in the last six months.

3.2.3 Inclusion and exclusion criteria for children and adolescents with STCP

This category of participants included children who were:

- aged between seven- and sixteen-years old,
- either spastic diplegia, hemiplegia, monoplegia or quadriplegia as diagnosed by the school paediatrician and noted in their school records,
- identified as either level I, II, III or IV according to the Gross Motor Function Classification Scale [GMFCS] (Palisano *et al.,* 2000) by a trained paediatric physiotherapist. Level V was excluded because these children were severely impaired, not ambulatory and therefore difficult to use in this type of research,
- certified by school physician or paediatrician to be healthy and not suffering from any other neurological condition, as established from their clinical record, and
- able to speak and understand English, for reasons stated above.

The exclusion criterion was limited to:

- children who had undergone any medical treatment less than six months before the study that would have impacted negatively on MAP's (e.g., Botulinum toxin injection, casting, surgical intervention such as dorsal rhizotomy and baclofen pump placement).

3.3 Sample size

According to Adcock (1997), for sample size in a continuous set of data such as the type generated in this study, the formula below may be used (Equation 2):

$$N = \frac{(t)^2 * (s)^2}{d^2}$$

In Equation 2: N = sample size for each of the groups, t = value for selected alpha level, $\boldsymbol{s}$ = estimate of standard deviation and d = acceptable margin of error. The changes in MAP's were selected to determine the required sample size as this was one of the main outcome measures of the study, and could have the greatest variance of all the parameters measured in the study. Therefore, for a hypothetical population size of 200, a sample size of 75 would be obtained by using the above formula. This is based on the calculation of a meaningful difference of, for example, 20 units and a standard deviation of 10 units for any one of the MAP's. With an accepted statistical significance of $p < 0.005$, groups of 11, 14 and 17 participants provided 80%, 90% and 95% statistical power respectively for the change in MAP. These figures provided statistical power to detect changes in one parameter between the two groups, therefore for the three components of MAP's (thickness, fibre length and pennation angle), together with EMG and the functional outcome tests, a composite number of five tests would be measured per group. Therefore a minimum of 15 participants multiplied by the five tests to be conducted gave an assumed sample size of 75 participants per group with a convenient 90 – 95% statistical power for the study. This sample size is also in line with the tables developed by Kasiulevicius *et al.* (2006) to provide adequate sample sizes in biostatistics and epidemiological studies. Similar numbers of male and female subjects were recruited for the STCP group and TD groups.

Using this determination of sample size, over one hundred learners were invited through their respective schools for inclusion in each of the two groups using letters of invitation along with the consent form. The final number of children who signed (by either themselves or their guardians) and returned the consent forms and who eventually met the inclusion and exclusion criteria came to 63 in the STCP group and 82 in the TD group. The difference in the final numbers between the two groups was not statistically significant ($p = 0.709$)

Since the GMFM test was to be conducted within the STCP group only and based on the above calculations for determination of the sample size, the selection of a total number of forty-two participants from the STCP group provided 80% statistical power (with 0.005 alpha levels) to detect differences between the groups. This number (42) comprises the minimum of ten individuals from each of the four levels of the functional diagnosis or disability levels (GMFCS I – IV).

Similarly, a total of thirty-six ambulatory participants from the STCP group (GMFCS I – III) were selected to undergo the PCI test. However, this cohort of individuals for the PCI test was age- and sex-matched with the same number from the TD group.

3.4 Questionnaire and instrumentation

The tools that were used in this study included a demographic questionnaire, measurement of height and weight in order to calculate the BMI, use of ultrasonagraphy to allow for measures of MAP's (impairments), the gross motor function classification system (GMFCS), gross motor function measure (GMFM) and the determination of the physiological cost index (PCI) to measure functional ability.

3.5 Demographic data

Demographic information - namely age, school grade, sex, GMFCS level and diagnosis - were extracted from the personal records at the schools with the help of the authorities and the therapist**.** Ultrasonography was used to determine abdominal muscle parameters (pennation angle, muscle fibre length and muscle thickness).

3.6 Anthropometric data recordings: (height, weight, body mass index, age, sex, grade and diagnosis)

3.6.1 Height

A stadiometer was used to measure height in centimetres. This instrument consists of a wall-mounted system where the horizontal arm is securely affixed and remains at an angle of 90 degrees, along with a steel ruler placed against a wall.

Subjects were asked to remove their shoes and stand with their backs, buttocks and shoulder touching the wall. To enhance reproducibility, they were told to stand as upright as possible with head positioned in the Frankfort Plane which is a plane in which the inferior border of the bony orbit of the eye is in line with the groove at the top of the tragus of the subject's external ear (Stanley, 1989). The horizontal arm of the measuring unit (usually a metal ruler) was used to depress subject's hair as much as possible, and remain at a rigid right angle to the measuring scale. Measurement was then recorded to the nearest 0.1cm. Measurement was recorded three times and the average used. In participants with CP who presented with a crouch stance, height was recorded once their knees were supported and passively extended by an assistant – the physiotherapist or school nurse present. Evidence of the reliability of

this procedure has been documented (Siminoski *et al.,* 2006; Gyi *et al*., 2004) and supported by the intra-rater analysis of this study (Appendix C1, Table 14). Occasionally, when an individual was wheel-chair bound, a tape measure was used to obtain the length of an outstretched limb which was added to the length of the trunk and head and neck in order to calculate the total body height with evidence of increasing reliability (Siminoski *et al.,* 2006; Gyi *et al*., 2004).

Measurements vary at different times of the day and intrinsic variability, regarded as precision errors have been reported with this type of data collection (Siminoski *et al.,* 2006). Same day inter- and intra-tester measurements between principal researcher and research assistant were also performed and results obtained subjected to Pearson's correlation co-3.3

3.6.2 Weight

Weight was measured using a SECA 959 digital chair weighing scale (UK). Participants wore their school uniforms and with their shoes removed, they were asked to sit comfortably in the digital chair weighing scale with feet rested on the foot rest pedals provided. Each subject sat as erect as possible in the weighing chair with their hands in their laps with the head facing forward. Prior to sitting on the digital chair, children were asked to void the urinary bladder in order to avoid any additional weight due to a full bladder. Recordings were taken in kilograms three times and the average taken. In order to ensure consistency, the measurements between the STCP and TD groups, the same digital chair was taken across from one special need school to the Open schools, which did not have this type of facility.

Validity and reliability of measures relies on adherence to guidelines by both participants and researcher. Measurements from the principal investigator were subjected to re-test in a cohort of children and this procedure was repeated for those obtained by the research assistant. These yielded inter- and intra-tester values respectively, which were subsequently subjected to correlation co-efficient analysis to validate the reliability of the weight obtained using this method and measuring tool.

The body mass index (BMI) of the subjects were calculated using the standard formula, mass (kg)/height (m) x height (m). The reliability of the method has been documented (Brener *et al.,* 2003. The validity and reliability of this calculation for the determination of BMI in this study is high (ICC > 0.70) for both groups. These results are shown in Appendix C1, Table 14.

3.7 Ultrasonic measures

A SIEMENS® ACUSONIC X150 ultrasound imaging machine (Munich, Germany) was used to verify the histo-architecture or muscle architectural parameters (MAP) abdominal muscles of these children and adolescents *in vivo*.

3.7.1 Measurement

Muscle architectural parameters (MAP) were taken for each of the four abdominal muscles in the resting and contracted states. For the resting state, also termed the neutral position, children were lying supine on the plinth with no activity. For the active state, children were asked to lie supine on the plinth and then asked to perform the following activities: (i) the upper limb on the more affected side (as determined from the child's medical record, by observation, and / or by asking the teachers and physiotherapist in charge) to be abducted fully at the shoulder joint, (ii) to tuck in the chin and lift head and neck slightly on the chest and (iii) flex the affected hip as far as possible in order to obtain a maximum voluntary contraction - MVC. The principal investigator (PI) handled the transducer head (ultrasound probe) while one of the research assistants, a trained neurodevelopmental therapist, issued the instructions to the participants.

Using the umbilicus as a landmark the ultrasound probe was placed two to three centimetres from the midline and then was panned around in a semi-circular fashion until the bulk of the image from the deepest lying abdominal muscle, transversus abdominis (TrA), was observed on the image screen. This position was marked on the skin with a marker pen in order to ensure that the probe was kept in this position for subsequent measurements. On many occasions, measurements for the rectus abdominis (RA) muscle was done separately as its fascicles were out of view from the image screen when the other three were being captured. In such circumstances, when it became necessary to take a sonograph of the RA alone, the transducer was placed approximately 2.5 cm superior to the umbilicus and perpendicular to the long axis of the RA muscle fibres. The scanning head of the probe was then oriented along the mid-sagittal axis of each of the rest of the three anterolateral abdominal muscle (external oblique, internal oblique and transversus abdominis), thus in somewhat oblique fashion. Thus, the pressure of the transducer was kept to a minimum by using a generous amount of the contact gel in order to obtain optimum values for muscle thickness.

Sonograms were then taken after having adjusted the depth gain compensation to optimise image quality. At rest and during contractions, the probe was held firmly against the skin at the same site over the muscle belly. Each of the sonographs being captured was a reflection of all the four abdominal muscles or the three anterolateral ones as viewed from the several representative images that showed one or more fascicles throughout their lengths as evidenced by the observation of the layers of aponeurosis and an interdigitation of the linea alba with a heavy white line on the image screen. No attempt was made to correct the positions adopted by each of the participants during the resting and active states, in order to avoid the potential effect of altering tonicity in the muscles. All sites along a muscle from which images were taken at rest were repeated during each child's maximum voluntary contraction (MVC) – the greatest extent to which a particular body part could be moved willingly, in order to establish whether the architecture of a muscle remained constant along and across the belly of muscle during contraction (active state).

All images obtained were stored on a personal computer and then analysed with ImageJ Microsoft version 1.46, 2011 edition (Richmond, Virginia, USA).

3.7.2 Calculations

Measurements of pennation angle and fibre length and thickness were derived from computer stored images using ImageJ processor in Microsoft version 1.46.

Raw sonographic images, (that is images captured without any muscle thickness measurements) obtained from all four muscles, both at rest as well as at all contraction intensities, were modelled as a two-dimensional parallelograms using the ImageJ processor in Microsoft version 1.46 (Huijing & Woittiez, 1984) to ascertain the veracity of muscle thickness values captured by the ultrasound machine. In order to do this verification based on the two-dimensional parallelogram model of muscle thickness values, the length of line/distance indicated with the ImageJ image processor was divided by 13.15 pixels to obtain a muscle thickness with the software. Thus:

Muscle Thickness (Th) = Length (i.e. distance between superficial and deep aponeuroses)/13.15 pixels (Huijing & Woittiez, 1984).

There was always a near perfect correlation or agreement between the verification process and the instant measurement of muscle thickness done with the freezing of the ultrasound calipers as shown by the high inter-rater coefficient scores (ICC > 0.70) in the STCP and TD

groups (refer to Appendix C3, Tables 1 and 2). However, the major geometrical assumptions made in using such planimetric models of representing these sonographs of the muscles as a two-dimensional figure, especially in determining pennation angle were that:

- aponeuroses behaved as rigid bodies and run parallel to each other, and
- muscle fibres ran straight between aponeuroses.

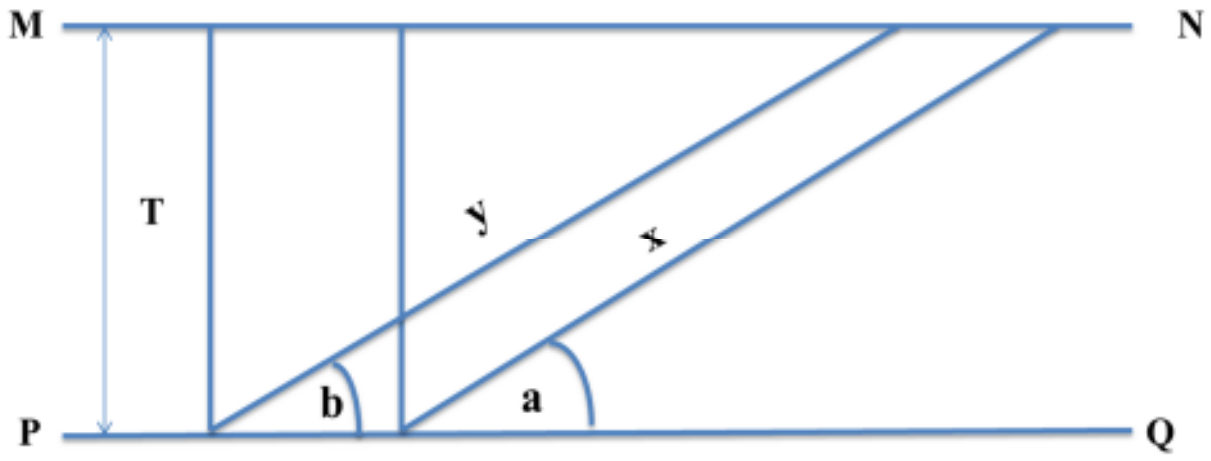


Figure 11: MN show superficial aponeurosis, PQ represents deep aponeurosis, MP or NQ represents muscle thickness, x and y represent muscle fibres and angles a and b represent their pennation angle

Muscle thickness (MT) was determined using an electronic caliper on a frozen image, by measuring the distance between the echoes of the superficial and the deep aponeurosis. The muscle thickness (*T* in Figure 11 above) was determined as the length of the perpendicular line drawn between the echoes parallel to the fascicles from the deep (PQ) up to the superficial aponeurosis (MN), and marked with an asterisk on the image by the clicking of the caliper button on the key board of the ultrasound machine (Ichinose *et al.,* 1995; Narici *et al.,* 1996; Fukunaga *et al.,* 1997). Since thickness varies along the length of a muscle, measurements were taken at three or four different points for a particular muscle according to the clarity of the image and the average was recorded for that individual.

The angle between the superficial and the deep aponeuroses echoes were defined as the muscle's *pennation angle (a* or *b* in Figure 11 above*)* (Rutherford & Jones, 1992; Kawakami *et al*., 1993).

By trigonometry trajectory:

Equation 3:

$$\text{PA} = \text{angle between deep aponeurosis and echoes of interspaces between fibres}$$

Equation 4:

$$\text{FL} = \frac{\text{muscle thickness (Th)}}{\text{sine of pennation angle}}$$

For Equations 3 and 4: PA is pennation angle, FL is muscle fibre length, Th is muscle thickness (Binzoni *et al*., 2001; Shorthand *et al.,* 2002).

3.7.3 Reliability and validity of ultrasonic measurements

The validity of this equipment has been documented in the literature with the most recent evidence from (Bunce *et al*., 2002; Ferreira *et al.,* 2004; Benard *et al.,* 2009; Unger, 2011) and test results all found to be appropriate for use in research and diagnostic analyses. For the purpose of this study inter- and intra-tester analyses were carried out between the principal investigator and the research assistants on the same day and on different days on a cohort of the participants. Correlation co-efficient for reliability was subsequently calculated to determine the suitability of this equipment as well as the repeatability of the measurement obtained. The test-retest results were presented in tables of Appendices C1, Tables 1-8 and C2, 1-8. All results showed good to excellent (ICC ratios > 0.70) correlation.

3.8 Determination of the patterns of abdominal muscle activation in children with STCP and TD by electromyography

3.8.1 Instrument

To address this issue an electromyograph was used to determine the activity in the abdominal muscles. The participants were instructed to lie down in the supine position without moving any body part (*resting state*) and raise the affected limb as high as possible (maximum voluntary movement – MVC), and as well as flexing or at least lifting the head while lying in the supine position (*active state*).

Due to the relatively thin nature of the abdominal muscles and their location in particular the depth of TrA from the skin, fine needle electrodes would have yielded optimum results. But the use of fine wire electrodes is not advocated in research (Ng *et al.,* 1998; Marshall & Murphy, 2003) especially in cases involving children therefore the use of the surface electromyography (sEMG) in this study. The sEMG equipment and technique are non-invasive and painless, and therefore their use and outcome tend to be readily accepted and generally safe.

The NORAXON® surface electromyography (sEMG) was used. This equipment uses disc coated silver-silver chloride electrodes which can detect algebraic sums of voltages associated with muscle action potential within their pick zones (Cram *et al*., 1998; Peper & Gibney, 2006). It is fitted with electrodes which are about 0.5 – 1.0cm in their wider diameter (Cram *et al*., 1998; Sella & Finn, 2001; Bolek, 2007). Each recording channel on this equipment is designed to detect activity from one muscle site and is composed of two active electrodes and a reference one (Cram *et al*., 1998; Peper & Gibney, 2006; Bolek, 2007). In estimating muscle activity from this study, the active electrodes were spaced with their centres about 2cm apart on the muscle. The difference in electrical charges between each active electrode and the reference one provides input to a differential amplifier with impedance of a common mode rejection ratio (CMMR) between 90 – 140dB (Peper & Gibney, 2006; Bolek, 2007). There are filters as part of the internal design of the NORAXON® sEMG equipment allow frequencies related to a muscle activity but reject those frequencies that are associated with electromagnetic noise (Cram *et al*., 1998; Peper & Gibney, 2006; Bolek, 2007). The signals obtained were viewed in their "raw" plus / minus form and then converted to a unidirectional signal in which the "plus-minus" waveform was rectified.

The qualities of this type of sEMG equipment include good signal resolution, minimal signal and image distortion, high CMMR (90 – 140dB), ample signal range and optimum sampling rate (Cram *et al*., 1998; Peper & Gibney, 2006; Bolek, 2007). Consequently, data obtained from this equipment were generally accepted as valid and reliable.

3.8.2 Procedure

In order to determine electrical activity in the abdominal muscles using surface electromyography (sEMG), all participants from both the STCP and TD groups were tested during the resting and active states. The muscle activity for three out of the four abdominal

muscles was measured separately during the resting and active states. For the rectus abdominis muscle (RA), the active electrodes were placed 3cm above the umbilicus and 3cm away from the median plane always on the right side but if unilaterally affected then on the left (*site A in fig 2 below*). The electrode sites were gently abraded with fine grain sand paper and cleaned with isopropyl alcohol (Hermens *et al*., 2000). The placement of the electrodes was done in accordance with standard procedures, (see Fig. 2 below) (Ng *et al*., 1998; Hermens *et al*., 2000). For the sake of convenience, the ground electrode was placed at the level of the twelfth thoracic spinous process (T12) for those participants with spastic diplegia and quadriplegia while this ground electrode was on placed on the patella of the non-affected limb for participants from the hemiplegic and TD groups. All the silver-silver chloride electrodes came prepared with a creamed electrode gel that made them to be self-adhesive in nature. However, electrode placements were further firmly maintained with adhesive cello-tapes until the end of the re-test session.

Prior to the collection of these data, participants were trained to reach paced activities within one minute with regard to tasks to be accomplished during active / contracted phases (head-up, chin-tugged-in and limb movements). Testing officially was initiated (usually a day or two after) when participants appeared to be consistent with tasks.

The sEMG signals were sampled at 1000Hz and saved on a personal computer for future analysis with a custom DELL / NORAXAM programme. Based on trial testing, patterns of sEMG activity in children were found to be variable across ten trials, and therefore the tasks were limited to a maximum of five after which the mean values of three consistent patterns were recorded as the sEMG value for a particular muscle. The more affected limb was identified by the neurodevelopmental therapist for the participants in the STCP group and while in the supine position on a plinth with the arms resting along the sides of the body, the children were asked to flex this limb as high forward as possible (maximum voluntary contraction – MVC). Full range abduction of the shoulder joint (upper arm movement) was also tested on the affected side and the EMG activity taken of the various abdominal muscles taken in turns.

Activity in the abdominal muscles with head and neck movements was also tested by repeating the same procedure but in a slightly different fashion, whereby subjects were instructed to tuck in the chin and then lift their necks / heads on to the chest. Limb movement also resulted in contraction of the abdominal muscles (Vasseljen *et al.,* 2009) and therefore

the EMG recordings related directly to MVC activity of the abdominal muscles. All these procedures were undertaken under supervision from their physiotherapist.

While a participant performs each of these activities, the active electrodes were placed on the muscle belly of a particular abdominal muscle with the average set of recordings per session being assigned to that specific muscle. The child repeats the same set of activities while the electrode placement is changed for another muscle. The most adequate site for the placement of an active electrode for each of the muscles in order to detect optimal activity in each muscle was illustrated in Figure 12 below. The transversus abdominis (TrA) was practically impossible to access using the surface electromyography techniques by virtue of the deep position of this muscle with respect to the anterior abdominal wall, which makes the detection of electrical activity of the TrA by the sEMG techniques difficult. Fine wire / needle technique would have been desirable but as the latter is not recommended for use in children for research purposes, the electrical activity of TrA was thus not measured. For the OE, EMG readings, the active electrodes were placed midway between the anterior superior iliac spine (ASIS) and the lowest point on the subcostal angle in the mid-axillary plane always on the right side but if unilaterally affected then on the left (*site B in fig 12 below*). Alternatively, the more lateral electrode was placed at the most lateral point in the mid-axillary line on the transumbilical plane on the affected side.

Electromyographic recordings for OI were taken with active electrodes at a point midway between the ASIS and pubic tubercle, about 2cm above the inguinal ligament in the mid-clavicular line always on the right side but if unilaterally affected then on the left (*site C in fig 12 below*). In the case of children from the TD groups, the active electrodes were placed at the anatomical sites on the right side.

The raw sEMG signals were first amplified 300 times by pre-amplified electrodes by default and then four times with the computer analysis. The signals were then filtered with 10 – 1000 Hz band per filter. All data were then filtered with a second low-pass filter at 16 Hz. A muscle onset of activity was defined as the point when EMG recording exceeded the baseline by two standard deviations for greater than 25ms and the software marks this point as the EMG traces. These were then visually inspected by the principal investigator (PI) and research assistant independently to ensure that subsequent outbursts or values / traces obtained by assigned tasks were related and could be compared to determine inter-tester

(between research assistant and PI) and intra-tester reliability (within day testing activity of the PI).

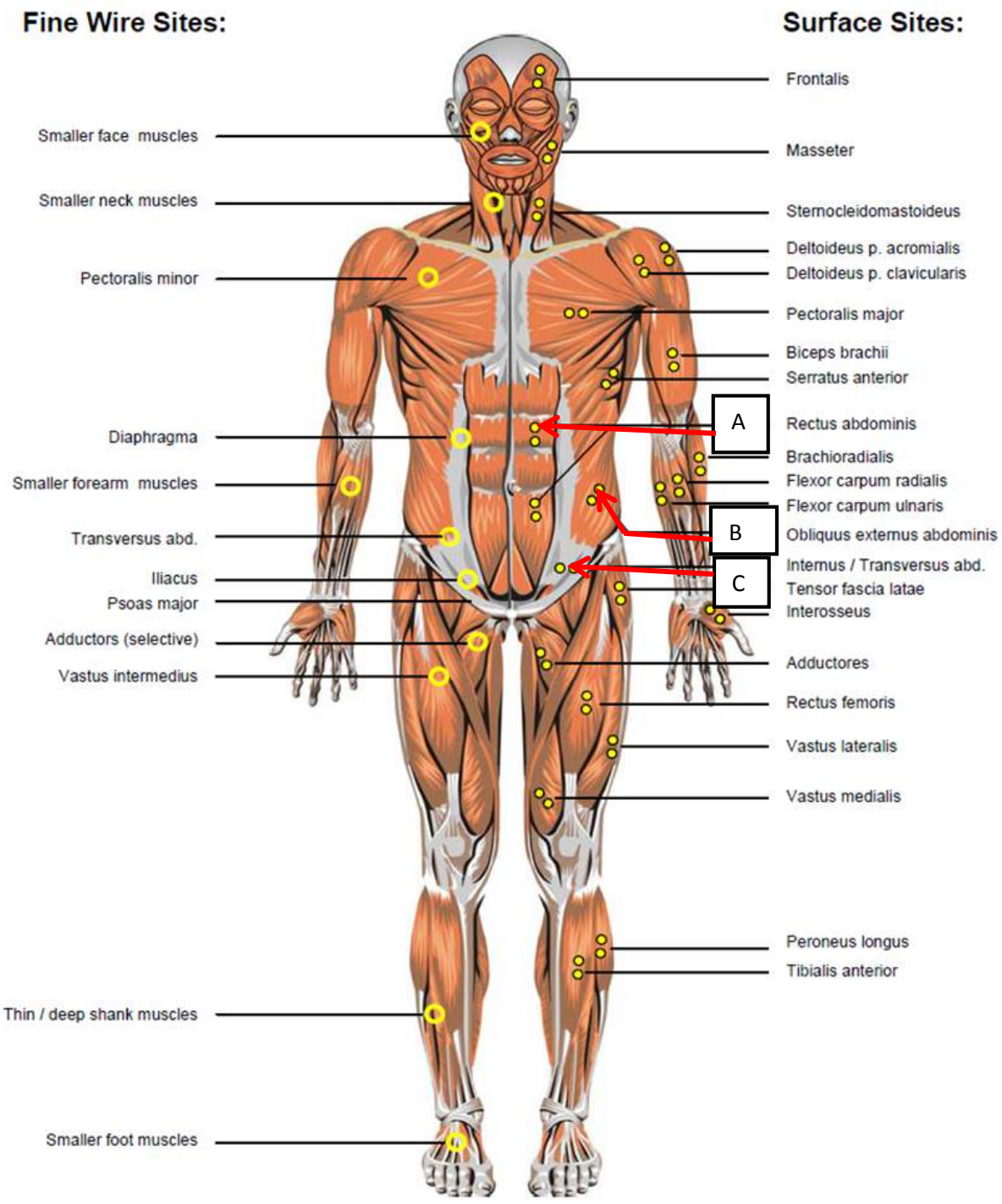


Figure 12: Sites for placement of fine wires electrodes in adults
Source: http:wg11.sc29.org/mpeg-v/wp-content/uploads/2012/09/emg1.png. 31/05/2013

3.8.3 Reliability and validity for sEMG

The fundamental validity and reliability of the NORAXAN (R) sEMG in biomechanical analyses have well been documented and accepted in research (Marshall & Murphy, 2003; Dankaerts *et al.,* 2004; Urquhart *et al.,* 2005). Values obtained were subjected to same day inter- and intra-tester analysis by the principal investigator and the research assistant and the correlation coefficients computed to determine reliability of this equipment. The results showed good correlation (ICC scores of > 0.7) and appear in Appendix C1, Tables 9 & 10 and Appendix C2, Tables 13-16.

3.9 Evaluation of functional outcome measures

3.9.1 The gross motor function measure (GMFM)

The GMFM was designed as a clinical assessment tool to measure change in gross motor function with children with CP. In this study the intention was to use this as a functional tool in the children with CP in order to relate their outcome scores to the abdominal muscle parameters as well as the recruitment pattern in these muscles rather than to use this assessment as a measure of change in gross motor ability. Even though the standard testing manual included items that had the potential to change as result of therapy, learning and natural development, the focus was on the correlation between functional outcome and muscle parameters. The GMFM is a reliable outcome measure to assess the motor function in children with severe muscle weakness (Avery *et al.*, 2003).

As the principal investigator was a neophyte in the administration of this test, it was important to ensure reliability of the results. Lessons from the GMFM Manual and Scoring Guidelines were used and repeated practice of the use of the techniques were performed on the same cohort of individuals (fifteen) over time prior to the actual testing sessions. Furthermore, some of the experienced GMFM users in the schools also provided criterion scores for the participants from which all of the performance practice scores were obtained and were evaluated for reliability in the main study. These structured and standardised efforts removed as much as possible individual interpretations about performance of the participants amongst the test raters (PI and two RA's), and ensured consistency (good reliability) in the application and scoring of the GMFM as an outcome measure in this study. The reliability of GMFM in general has been documented (Palisano *et al*., 2000; Rosenbaum *et al.*, 2002).

The test was conducted by following the instructions outlined in the testing manual for this measurement tool (see Appendix B1). Each subject was tested without shoes or orthotics if applicable. Participants were subjected to a range of domains in the test guideline as determined by his or her ability to complete such tasks and therefore certain items were selectively omitted for some participants. If a particular posture prevented a child from performing an item, a score of zero was recorded for that item. If the investigator could not elicit a physical response from a child, a score of zero was assigned for that item. Both the principal investigator and the therapists of the schools conducted these tests on each subject over a two week interval and the results obtained were evaluated for inter- and intra-rater correlation co-efficient. These results are presented in Appendix C2, Table 17.

The actual GMFM test by its development and validation was designed as a criterion-referenced observational test / tool for children with CP (Palisano *et al*., 2000; Russell *et al.,* 2000; Rosenbaum *et al*., 2002) and therefore by convention, both the principal investigator and the therapists acted passively by scoring the participants based on their performances. The 88 items of the GMFM were measured by observation of the child and scored on a four-point ordinal scale, as set out in the manual (see Appendix B1). A score of *0* correlates to child did not initiate the item, *1* means that a child merely initiates an item (below 10% of the activity), *2* indicates that a child partially completed an activity (from 10% to below 100%) and a score of *3* denotes that a child completed the activity fully (100%). Scores for each dimension are expressed as a percentage of the maximum score for that dimension and the total score for each participant was obtained by averaging the percentage score across the five dimensions as indicated in the table below (Table 1). Items were grouped within each dimension according to the degree of difficulty, arranged from easiest to most difficult, for ease of administration. Table 1 shows the five GMFM dimensions arranged in order of increasing difficulty, the dimension names, the number of items in each dimension and finally the maximum score attainable in each dimension:

Table 1: Breakdown of GMFM dimensions, description, item numbers and scores (adapted from: www.fhs.mcmaster.ca/canchild)

GMFM dimensions	Dimension name	Number of items	Maximum Score
A	Lying and Rolling	17	51
B	Sitting	20	60
C	Crawling and Kneeling	14	42
D	Standing	13	39
E	Walking/Running/Jumping	24	72
Total		88	264
Adjusted total		78	234

3.9.2 The physiological cost index (PCI)

Using the available literature, the principal investigator was fully informed about how to conduct the PCI test (Nene, 1993; Raja *et al*., 2007) and analyse the resulting data, as well as receiving training from one of the co-supervisors of this study who was well versed in the use of the PCI test. Each of the participants was asked to walk at a self-selected comfortable pace for a distance of 50 metres measured using an outstretched tape measure that was glued with cello-tape to the floor in the corridors or walkways of their respective schools. The time taken to complete this distance was recorded in minutes and the gait / walking speed determined as shown below. The children who were selected for this session were asked to refrain from eating for at least two hours before arriving for this session and were also instructed to wear comfortable walking shoes.

Conventionally, a treadmill is the most appropriate instrument for measuring the gait or walking speed, in which a chosen set of speed is recorded for each individual for a particular duration. However, since the study was designed for school going children during school hours and also as a result of the absence of treadmills in the schools, this was not possible.

The pulse rate / heartbeat for each child was measured with a portable paediatric auto digital sphygmomanometer (MO760) and recorded both at the beginning and the end of this exercise. This instrument is user-friendly and comes with a single operation button for inflation, deflation and taking measurements.

After a short briefing and familiarisation of this session each subject was asked to sit quietly for at least five minutes on a comfortable chair for their heart beat to reach a steady state. With each subject seated and the left arm resting horizontally in the supine position on a table, the cuff of the sphygmomanometer was guided onto the upper arm and allowed to rest about 2 – 3 cm proximal to the crease in the cubital fossa for about two to three minutes. The machine immediately auto inflates the arm, measures the systolic and diastolic pressures as well as the pulse rate and the results displayed on the screen. A steady-state heart beat was attained when the readings taken within one minute apart were within five beats of each other. About five to ten minutes resting period was allowed between the initial heart rate measurement and the commencement of the walking exercise in order to bring the measured values of each individual as close as possible to normal values. This short resting period also was meant to eliminate any false heart rate values that maybe observed due to anxiety from the participants. Once the heart rate readings were in the steady-state, the children began the test while walking along the 50-metre track. The heart rate was recorded at the completion of the 50-metre stretch. The entire test was repeated either three or four times, according to the compliance of the subject, and the average value of the readings that were recorded for each participant was calculated. All participants were assessed twice on the same day by the principal investigator to evaluate the intra-rater reliability. A research assistant also measured all the subjects under the same conditions on different days and the PCI values between the two raters were compared to establish inter-rater reliability. The time taken to complete the 50 metre walking distance was recorded with a portable Olympus electronic timer clock after the subject returned to the rest position for the final heart rate to be measured. The walking speed, i.e. the time taken to cover a set distance of 50 metres measured in m/min, of each participant was then evaluated as (Equation 5):

$$\text{Walking speed} = \frac{\text{Distance (m)}}{\text{Time (min)}}$$

The average PCI value recorded for each individual in heart beats per metre was obtained using Equation 1 in section 1.9.

3.10 Reliability testing

3.10.1 Inter-tester reliability

There were two assistant researchers (AR's), namely a physiotherapist and an occupational therapist, serving as professionals in the special needs schools and who provided support services for the study on testing days. A pilot study was conducted by the AR's with fifteen or twenty participants (according to the test) from each group in order to confirm that standard procedures were being used by both researchers.

With regard to the results for MAP's, one of the AR's was knowledgeable in the use of the ultrasound equipment and was the main operator of the transducer head while the other AR issued instructions to learners as well as monitoring their compliance during inter-tester sessions.

Apart from the use of the EMG equipment, all the other sets of tests form part of routine exercises performed by the AR's in the management of STCP cases. Consequently, the inter-tester findings from the AR's provided a reliable index for the testing instruments of the current study. The suppliers of the EMG equipment offered an intensive training workshop to both the principal investigator and the AR's for the use of this equipment before the commencement of this study.

The intra- and inter-tester measurements were performed after about a week of testing by the PI and all the results showed a high correlation with the findings from the PI as indicated by high ICC scores (> 0.70) and the analysis tabulated and presented in the Appendices C1, Table 11 and C2, Table 18 respectively.

3.10.2 Intra-tester reliability

Routine training workshops on the use of equipment characterised the preliminary phase of this study by the principal investigator. Tutorials and repeated lessons on those test items that involved clinical observational skills were also given to the PI by one of the co-supervisors of this study. Additionally, pilot studies of fifteen participants were undertaken as a way of ensuring standardisation of the clinical practice and protocols.

Apart from the pilot studies meant to be a familiarisation of the testing skills acquired by the PI, for each of the major test (anthropometric, MAP, EMG, GMFM and PCI measurements), fifteen participants from each group were measured twice a day, done twice per week,

separated by three days. These results served as intra-tester reliability for the study and also to consolidate the lessons learnt from tutorials and training workshops on the use of the equipment. The intra-tester measurements are thus meant to establish reliability or repeatability of the procedures used in the main study. The results of each of these intra-tester analyses are shown in the tables of Appendix C1.

From the test-retest analyses all the test items, good to excellent intra-observer reliability was obtained, with alpha levels > 0.70 (refer to tables of Appendix C1). This indicated that there was minimal measurement error occurring in the use of the test instruments by the PI. While the sample size was small in the test-retest measurements (N = 15), therefore limiting the results, the instruments and procedures used for the study appear to be sensitive enough to measure the parameters outlined and to identify any difference between the groups.

3.10.3 Analysis of inter- and intra-tester reliability

Several steps were undertaken to ensure that the inter- and intra-tester results were valid and reliable. Several of these have already been discussed (above) and further points are dealt with below.

When considering the instrumentation (such as the stadiometer, weighing chair, ultrasonograph, electromyograph, sphygomomanometer, electronic timer) the calibration was not an issue for the PI because the instruments were either digital and therefore self-calibrating when switched on, or did not require any form of calibration. Apart from the stadiometer, the electronic design or digital nature of the calibration in the instrumentations used made manipulation and repetition of test procedures easy. Although the stadiometer was non-digital, its user-friendly application ensured the validity of the measurements, as documented by Buyken *et al.* (2005).

In order to ensure repeatability, both PI and AR's adhered exactly to the correct procedures as provided in each testing manual and / or instruction handbooks in the handling of the instruments. Procedures for each measurable item were repeated in an identical way on each of the participants and supervision on compliance to instructions by the subjects was monitored in turn by both the PI and AR's. Subjects were placed in standard positions and performed activities that were as close to identical as possible for each test item in order to minimise all possible variations between the subjects in the measurement of parameters by the investigators (PI & AR). If the procedures for either the tester or the participant were not

carefully adhered to, the outcome was an "*error*" score. With regard to reliability of the EMG activity for example, results from a previous study indicate that this is site-dependent (Marshall & Murphy, 2003), therefore the placement of the active electrode for all participants was carefully adhered to. Additionally, confounding factors such as the amount of adipose tissue, reported to affect the reliability of signals from the RA and EO (Hodges & Richardson, 1999; Marshall & Murphy, 2003), were eliminated during the recruitment of subjects for this study (BMI > 25 kgm^{-2} excluded). In the case of the ultrasound equipment, non-compliance amounted to "*no image*" on the monitor. All the pre-testing preparations were identical for each child, for example the emptying of the urinary bladder, no food for two hours, removal of shoes and relaxing before baseline physiological parameters were measured.

For height, weight, time and muscle thickness, the measurements were repeated either three to four times by each tester on a participant and the average was then calculated and used as the measurement for that subject. In the case of those test items that involve calculations (e.g. BMI, PCI, as well as FL and PA from the MAP category), baseline or initial scores recorded in the field notebook were put into the personal computer using Excel® (Microsoft) software, were checked for accuracy, and thereafter entering the appropriate mathematical formula and copying this formula to all relevant cells, the programme was responsible for the calculations.

Finally, the test-retest results as shown in the Appendix # were further validated and made reliable by age-matching the data from the STCP and TD groups for each test item.

The available literature is relatively vague on the most appropriate test for analyses when investigating the reliability of repeated measurements. However, when a comparison between two raters or "occasions" is conducted a correlation coefficient is typically calculated (Altman & Blind, 2005). The most widely used type of correlation co-efficient is the Pearson *r* (Bland & Altman, 1995 a & b; Altman & Blind, 2005). However, in the current study since the sample size for the test-retest analysis was small (N = 15), the Pearson *r* could over-estimate the test-retest correlations, therefore, the Intra-class correlation co-efficient (ICC) was used.

The ICC is reported to conceptualise the ratio of variance between groups to the total variance and is documented to be sensitive to changes in both the order and the magnitude of repeated values (Bland & Altman, 1995 a & b). The ICC agreement compares each

individual measurement and not just the group means, whereas the ICC consistency identifies the consistency in measurement errors (Bland & Altman, 1995 a & b).

In the current study, ICC agreement (using STATISTICA version 11, www.stat.com) was selected as the preferred means of analysis for the inter- and intra-tester studies with the participants in both groups. As this particular test was aimed at determining the reliability of the measuring process and the analysis of each measurement between testers, the smaller sample size was deemed appropriate in order to ensure that any bias or systematic error was identified.

3.11 Study procedure

Ethic approval was obtained from the Faculty's Human Research and Ethical Committee (HREC REF: 490 / 2011). Permission was received from the Department of Education of the Western Cape and from the principals of the participating schools. The schools for children with special needs also serves as some of the peripheral learning centres for clinical and rehabilitation undergraduate students of the faculty of health science, therefore a collaboration exists between the faculty and these schools, hence accessibility to the authorities of these schools was facilitated on that basis.

The physiotherapists working at the schools identified children who met the inclusion criteria and information sheets and informed consent forms were sent home with the children for their parents to fill in and reminders were sent if the forms were not forthcoming (refer to Appendix A for the appropriate ethics documents). All children in the appropriate age groups were given information sheets to take home. Once permission was received from the parents / guardians and the children, data collection at school premises commenced.

An unused classroom or office was temporarily equipped with a plinth and used for the duration of the study at the two co-educational schools where children from the TD group were recruited. At the schools where children with STCP were selected for participation, a small private therapy room in the Physiotherapy Department was temporarily equipped with a plinth and used also for the duration of the study. In some cases data collection days were scheduled to coincide with the off-duty days of the physician-in-charge of the schools. This was to make room for data collection to take place uninterrupted in the office of the school physician. Participants were tested only during school hours. Children from the same class were allowed to accompany each other during testing sessions. Since testing of abdominal

muscles required children to expose their abdomens, there was also the presence of the school nurse or the paediatric neurodevelopmental therapists or the research assistants all of who incidentally were females or in the case of public schools, a female teacher was always present alongside the principal investigator.

The data collection started with the measurement of anthropometric parameters of subjects i.e. height, weight and body mass index (BMI). This was followed by ultrasonography. Measurement of muscle activity using EMG was also done at the school premises shortly after obtaining the ultrasound scans. In many cases, the subjects became too exhausted after going through two different test items or we ran out of time leading to the rescheduling of a new day for the assessment of their gross motor function measure (GMFM) and physiological cost index (PCI). This was appropriate as the determination of GMFM and PCI in these learners was elaborate and more time consuming than the measurement of their anthropometric and demographic data. The age and distribution of the various STCP subtypes were the main parameters considered in the selection of participants for these two outcome tests across all three schools. In addition, the non-affected sides of children with STCP were also measured to serve as contrast in the cases of those individuals diagnosed with hemiplegia.

3.12 Statistical analysis

Entry of data was first of recorded in a field notebook and subsequently transferred to a data collecting sheet drawn up in "Microsoft Excel" allowed for the recording of demographic, anthropometric and outcome measures for each subject.

STATISTICA software package, version 11 (2012) was used to analyse the data. Descriptive statistics including means and standard deviations (SD), medians and ranges were presented. The Chi-Square test was used to compare the sex distribution between the STCP and TD groups. A Spearman's Rank Order correlation between demographic data and MAP's was performed to establish the level of correlation between age, body mass index and between the MAP's and functional parameters. In almost all cases age was a predictive factor for the observed scores of the parameters. In addition, the STCP group had more older children than the TD group and therefore, the respective scores for each individual for each parameter were divided by the age of that participant in order to standardise or normalise the variables. The age-normalised data were used whenever the two groups were compared. The raw data were used for within group comparisons. In order to determine the use of an appropriate statistical

test, all age-normalised data were subsequently tested for normality by using the Shapiro-Wilk test. Since almost the entire set of data generated was found not to be normally distributed, the Kruskall-Wallis ANOVA was used to compare the multiple independent sets of data while the Mann-Whitney U test was mainly used to rank and display the *z*- and *p*-values of the two independent sets of data from the STCP and TD groups.. Occasionally, in the case of those data found to be normally distributed an independent t-test was used to compare the mean values of the parameters between the children from the STCP and TD groups. The level of significance for all statistical tests was set at 0.05.

Table 2: A table showing the statistical tests used for the analyses of data

Parametric	**Non-parametric**	**Purpose**
Mean, standard deviation,	Median, range	To describe the sample and the parameters measured
95% Confidence intervals		To determine the precision of the estimates, e.g. Muscle thickness difference between resting and active states
Shapiro Wilks		To determine whether the data were normally distributed
	Chi-square	To determine association between categorical variables, such as sex, group (TD or STCP), GMFCS level
Independent t-test		To determine if there was a significant difference in the mean scores of the parameters
	Mann-Whitney U	To determine if there was a significant difference in the rank ordering of ordinal or non-normal numerical data, such as age, height and weight
	Wilcoxon matched pairs test	To test for differences in various parameters within all groups, specifically in the children with spastic hemiplegia (from affected to unaffected side)
Pearson's r	Spearman's rho	To establish if two sets of data were correlated, e.g. BMI and muscle thickness or Age and change in EMG activity from rest to active state
	Kruskall Wallis ANOVA	To determine if the mean ranking of different parameters differed across, e.g. the GMFCS levels and distribution of CP

Chapter 4 Results

4.1 Introduction

The demographic and condition related information is presented first. This is followed by the descriptive statistics relating to the muscle parameters and then a comparison of these parameters between the different groups. The relationship between muscle parameters and EMG will be analysed. In the subsequent sections of this chapter the relationship between muscle parameters and muscle function will be presented.

4.2 Subjects

A total of over two hundred participants (more than one hundred in each group) met the inclusion criteria and were invited through the distribution of consent forms. Sixty-six children together with their parents/guardians, from the STCP group signed and returned their forms whereas in the TD group eighty-six children and adolescents agreed to take part in the study. At the time of commencement of data collection, the number of children in the STCP category reduced to sixty-three as two of the participants from one of the schools had discontinued schooling and in another school, one other participant had undergone surgery through the anterior abdominal wall and was consequently excluded from the study. After the collection of the demographic data of all the participants, the total number in the TD group dropped to eighty-two as four of these learners (three males and one female) had a BMI value of greater than 25 kgm^{-2}. The flow-chart in Figure 13 below shows the recruitment and follow-up numbers, together with the respective tests and analyses administered to each group.

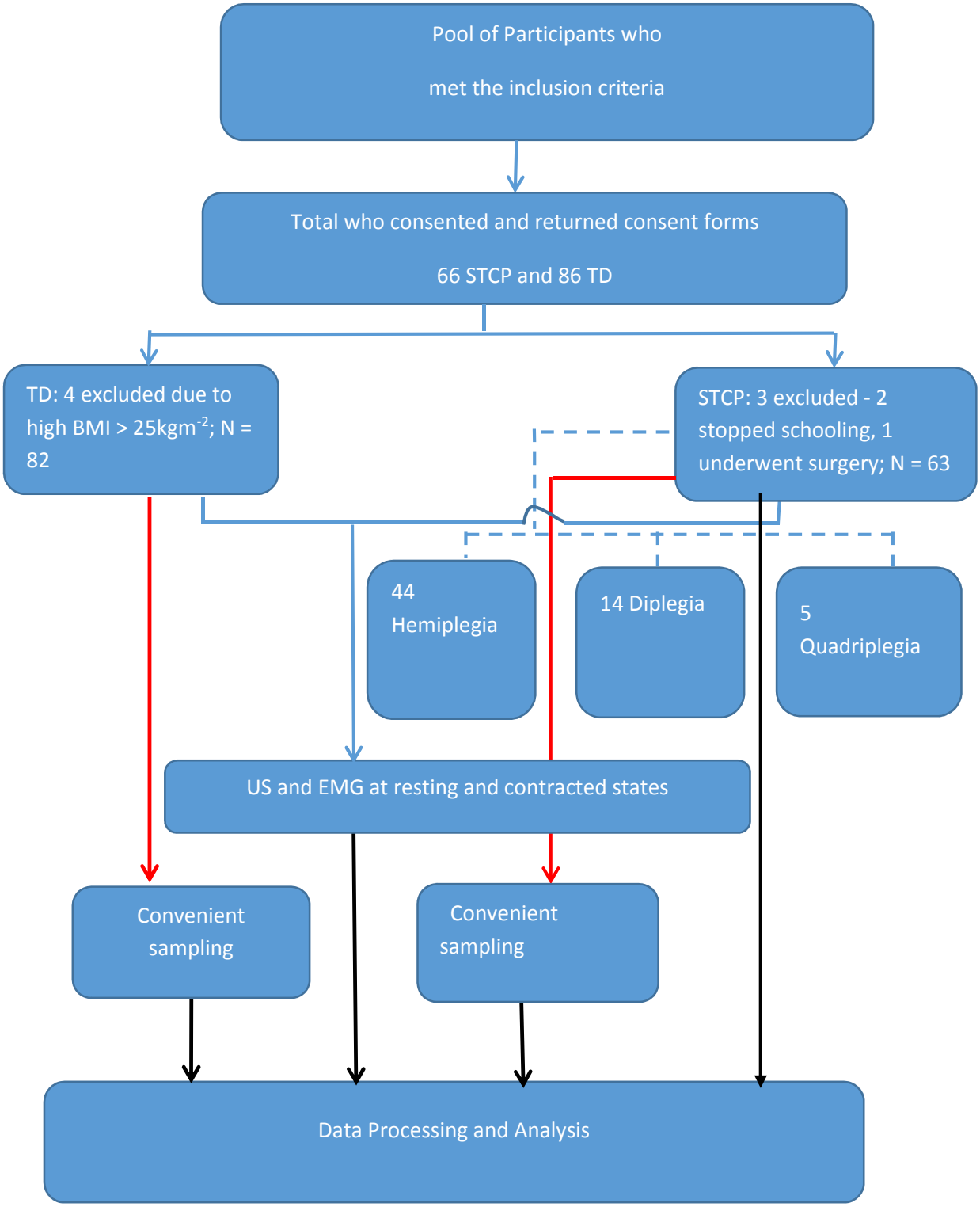


Figure 13: Flow chart of recruitment and follow-up

4.3 Description of samples

4.3.1 Total sample

The final sample included 145 children drawn from five schools in Cape Town, three of which were special schools for children with disabilities and the other two schools were for children with typical development, Open schools Table 3. One of the special schools also offered tuition for both children with disability and typically developing children therefore some of the participants from the two groups were sampled from this school. There were 63 (43.4%) children with STCP and 82 (56.6%) typically developing children. The mean age of all the children was eleven-years and three-months-old (Standard deviation (SD) = 3.0, range 7-16). Of the total sample, 53.8% were male and 46.2% were female.

Table 3: Schools from which children were drawn (N = 145)

		Count	Percent
STCP	**Special School 1***	27	18.6
	Special School 2	16	11.0
	Special School 3	20	13.8
TD Children	**Open School 1**	48	33.1
	Open School 2	15	10.3
	Special School 1*	19	13.1

* Provided participants for both CP & TD groups.

The descriptive statistics relating to height, weight and BMI are depicted in Table 4.

Table 4: Height, weight and BMI (N = 145)

	Mean	Minimum	Maximum	SD
Height (cm)	141.5	112.5	181.0	16.7
Weight (kg)	39.2	18.5	70.8	11.5
BMI (kgm^{-2})	19.1	13.0	24.0	2.6

4.3.2 Distribution of GMFCS levels among the STCP group

As shown in the Table 5 below, more than half, 54% (34 out of 63) of all the STCP participants were able to move around freely. That is to say more than half of the total STCP population was drawn from level I of the GMFCS level. The other disability levels, GMFCS II, III and IV were only sparingly represented 17%, 13% and 16% respectively. Note that the most severely affected STCP type namely the GMFCS Level V was not part of the inclusion criteria. Except for the participants in the spastic quadriplegia subtype group in which no GMFCS levels I and II were recorded, all the GMFCS disability Levels were represented in the hemiplegic and diplegic sub-groups. About two-thirds of the participants in the hemiplegic subtype (29 out 44) were mildly affected (GMFCS level I).

Table 5: GMFCS distribution of STCP cases

LEVEL	Hemiplegia	Diplegia	Quadriplegia	Total for level
I	29	5	0	**34**
II	9	2	0	**11**
III	3	4	1	**8**
IV	3	3	4	**10**
All Groups	**44**	**14**	**5**	**63**

4.3.3 Comparison between children with STCP and those from the TD group

The sex distributions, ages and BMI were compared between the two groups. These were greater in the males in both groups Table 6 but the distribution was not statistically significantly associated with each group (Chi-square = 0.140, df = 1, p = 0.709).

Table 6: Sex distribution (N = 145)

	Male	Female	Total
STCP	35	28	**63**
	55.6%	44.4%	
TD	43	39	**82**
	52.4%	47.6%	
All groups	**78**	**67**	**145**

4.3.4 Comparison of age, height, weight and BMI between the two groups (STCP: N = 63, TD: N = 82)

The age, height, weight and BMI of the two groups and the Shapiro Wilk test for normality are given in Table 7 below. As all except BMI were found not to be normally distributed, non-parametric tests were used to compare these variables.

Table 7: Comparison of age, height, weight and BMI between the two groups

	Mean STCP	SD STCP	SW*	P value	Mean TD	SD TD	SW	P value
Age (years)	11.9	2.92	0.928	0.001	11	3.04	0.907	< 0.001
Height (cm)	139.2	16.04	0.966	0.076	143.3	17.13	0.94	0.001
Weight (kg)	39.7	10.28	0.959	0.036	38.7	12.38	0.956	0.007
BMI ($kg.m^{-2}$)	20.1	2.16	0.984	0.079	18.4	2.62	0.984	0.413

There were no significant differences in age ($p = 0.087$), height ($p = 0.213$) or weight ($p = 0.457$) between the two groups Table 8. The children with STCP were both shorter and heavier than the children in the TD group, and therefore the children with STCP had a significantly greater BMI compared with the latter group ($p < 0.001$).

Table 8: Comparison of Mann-Whitney rank sum of age, height, weight and BMI between the two groups (STCP: N = 63; TD: N = 82)

	Rank Sum - SPTCP	Rank Sum – TD	U	Z - adjusted	p-value
Age/years	5026	5560	2157	-1.71	0.087
Height/cm	4287	6299	2271	1.24	0.213
Weight/kg	4786	5799	2396	-0.74	0.457
	t-value				
BMI	-4.34				$p < 0.001$

Although there was no significant difference in the ranking of the ages of the two samples, histograms showed that there were younger children in the TD group than in the STCP group (Figure 14).

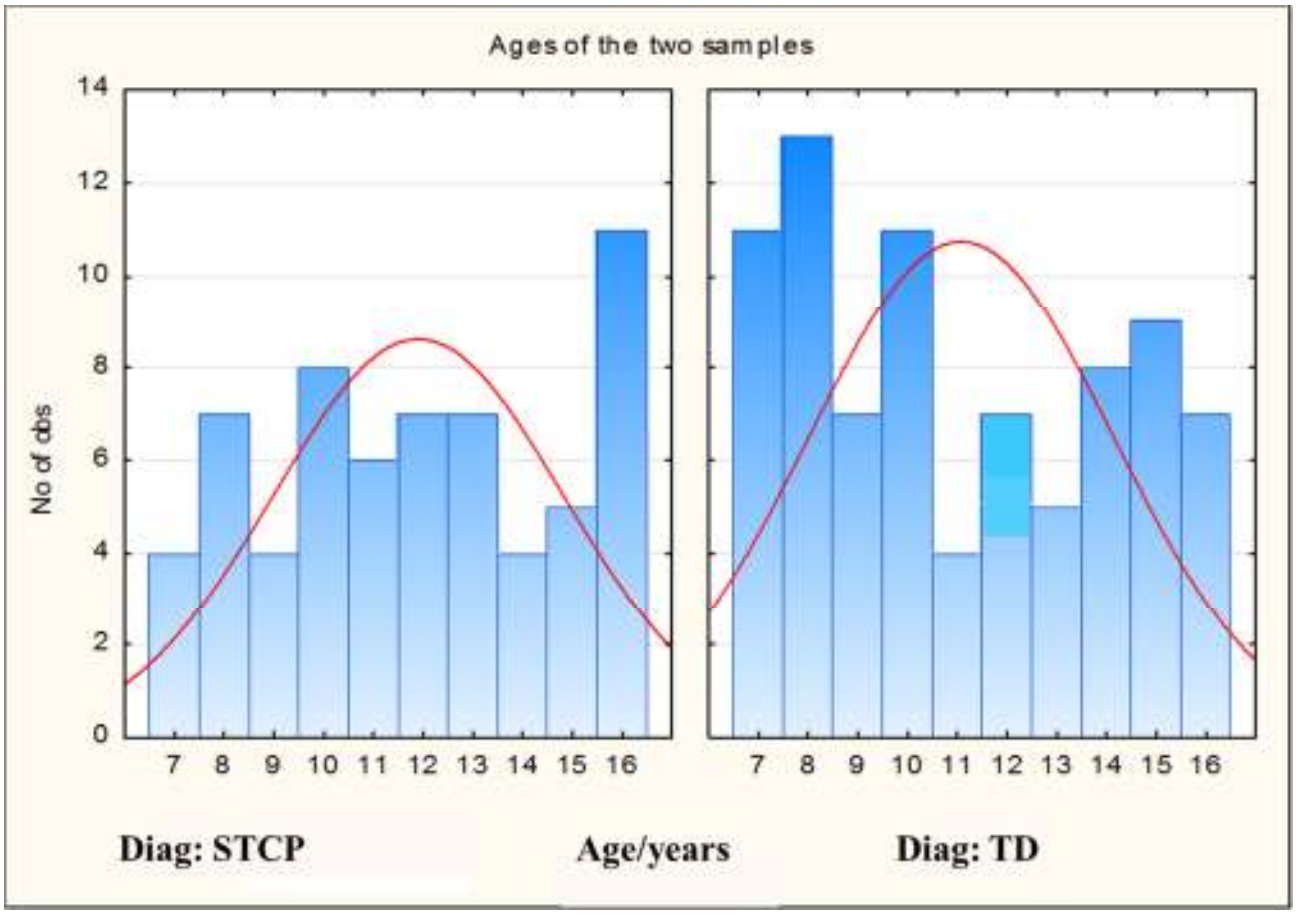


Figure 14: Histogram of the ages of the two groups (CP N = 63 and TD N = 82)

4.4 Muscle thickness

Most of the muscle parameters were not normally distributed. In this section the raw data for muscle thickness are presented. The correlation between muscle thickness in the resting and active states was calculated. The correlation between age and muscle thickness was found to be strong and consequently muscle thickness values were normalised for age. The differences in normalised scores were compared for both states across the two groups. Finally the

difference between the normalised thickness of the relaxed and active states was calculated and this change in thickness was then compared between the two groups.

4.4.1 Raw data: muscle thickness

In both groups of children, for abdominal muscles in the resting and active states, the RA was the thickest, followed by IO, then EO and finally TrA, both at rest and when active (Table 9). In addition, the EO, IO and TrA became thinner after contraction in STCP children compared to those of the TD group, which were thicker on contraction. The exception, therefore, was the RA which was thicker on contraction in both groups of children.

Figure 15 below shows a sonograph with markings (+ *sign*) showing the inter-fascial boundary between individual muscles. The vertical line indicated by MT specifically represents the IO thickness, while the obliquely running FL represents TrA fibre length.

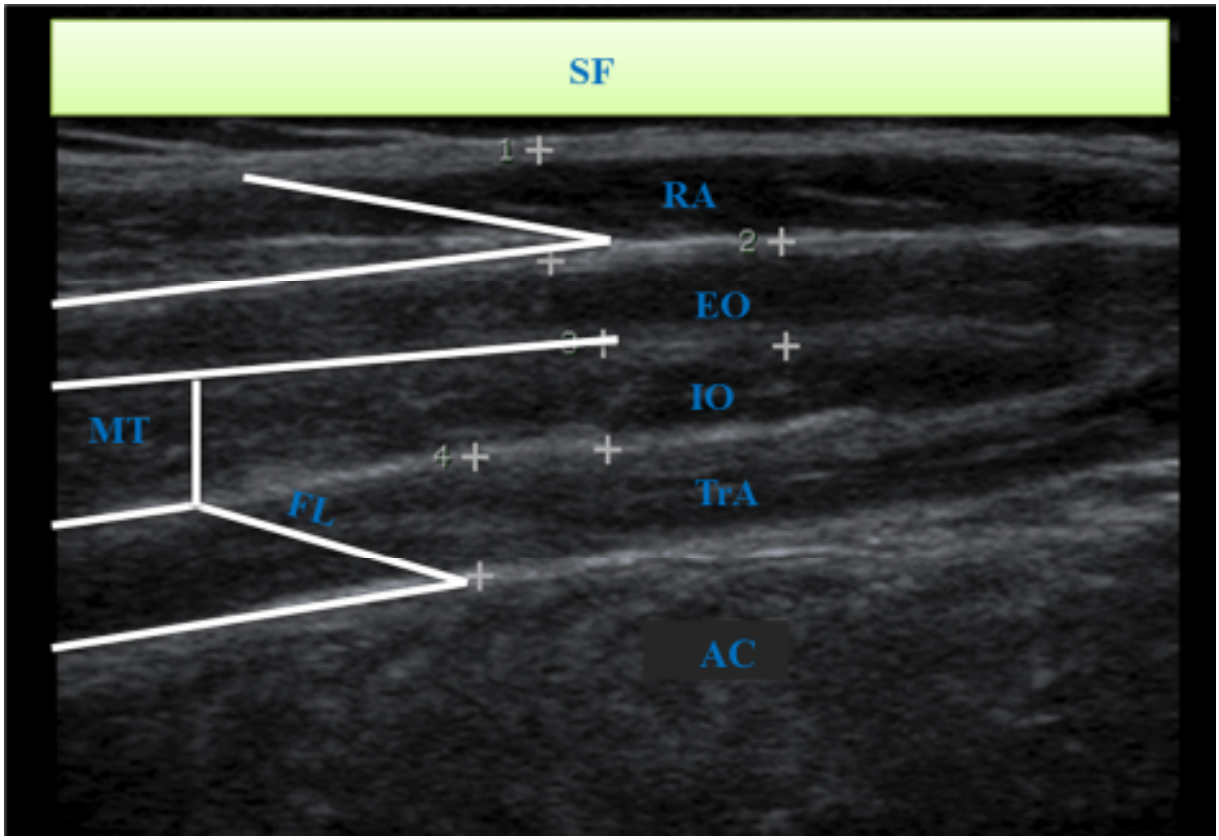


Figure 15: Picture showing all four abdominal muscles and the parameters measured by the US. SF = skin and superficial fascia, RA = rectus abdominis, EO = external oblique, IO = internal oblique, MT = muscle thickness, TrA = transversus abdominis, FL = fibre length and AC = abdominal cavity.

Figure 16 below shows the relative thickness of the three anterolateral abdominal muscles (EO, IO and TrA) of an individual with STCP during the active state. Note the aponeurosis creating demarcations between individual muscles.

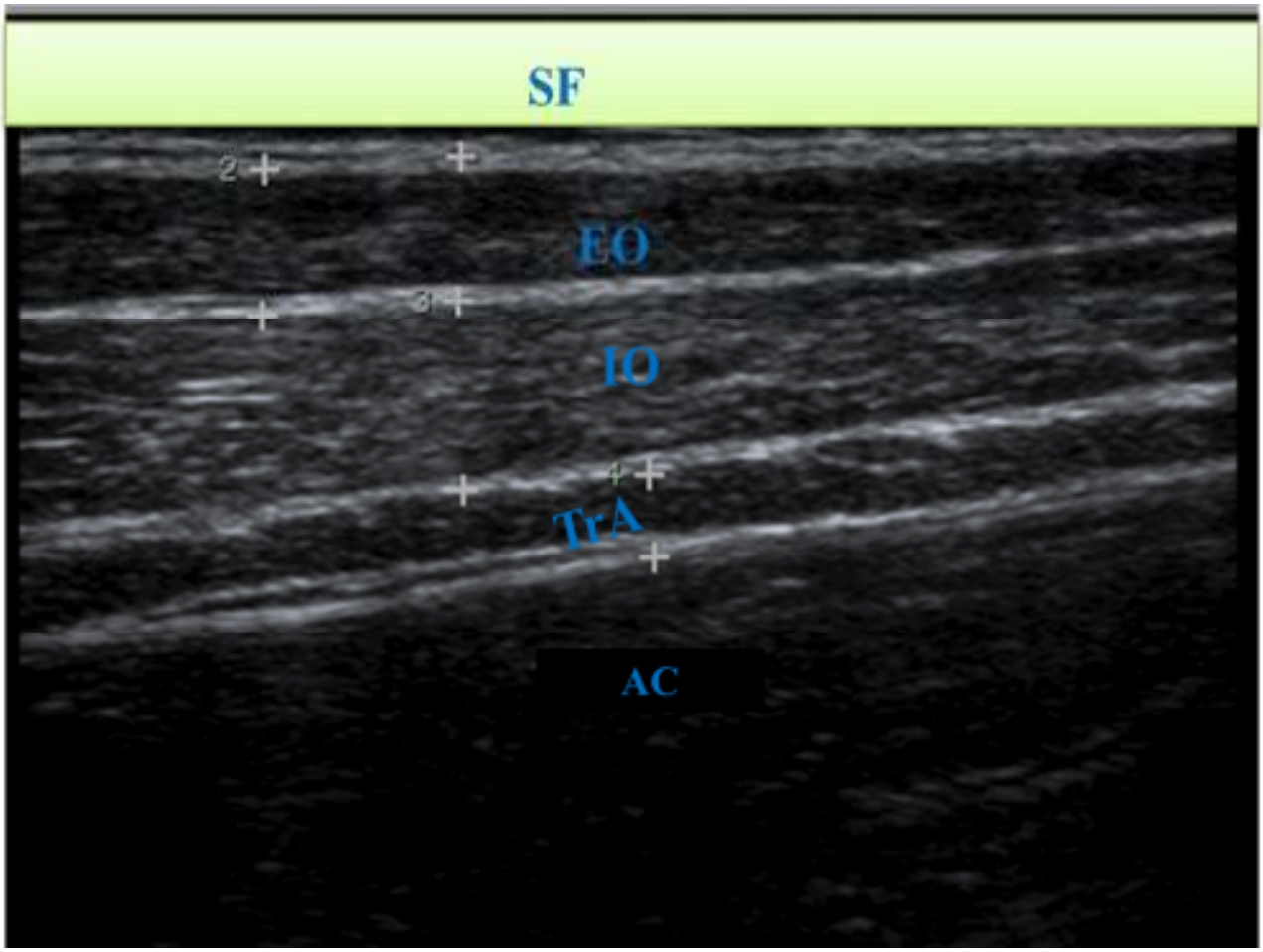


Figure 16: Picture showing the three anterolateral muscles. SF = skin and superficial fascia, AC = abdominal cavity. The RA is out of view.

Table 9: Muscle thickness at rest and in contraction, tests for normality and the difference between the resting and contracted states (STCP: N = 63, TD: N = 82)

		Mean	SD.	SW*	P value	Difference between resting and active**	SD of difference	95% CI of difference
STCP	**EO Th R (mm)**	3.6	0.5	0.979	0.357			
	EO Th Ac (mm)	3.4	0.5	0.948	0.010	-0.3	0.2	-0.32- (-0.23)
TD	**EO Th R (mm)**	3.1	0.5	0.915	0.000			
	EO Th Ac (mm)	3.3	0.5	0.927	0.001	0.2	0.2	0.17-0.24
STCP	**IO Th R (mm)**	4.8	0.7	0.928	0.001			
	IO Th Ac (mm)	4.4	0.7	0.939	0.004	-0.3	0.2	-0.39-(-0.27)
TD	**IO Th R (mm)**	4.3	0.5	0.969	0.110			
	IO Th Ac (mm)	4.5	0.5	0.949	0.011	0.2	0.1	0.18-0.23
STCP	**TrA Th R (mm)**	2.9	0.5	0.909	0.000			
	TrA Th Ac (mm)	2.6	0.5	0.932	0.000	-0.3	0.1	-0.34-(-0.26)
TD	**TrA Th R (mm)**	2.1	0.5	0.939	0.001			
	TrA Th Ac (mm)	2.4	0.5	0.926	0.000	0.3	0.1	0.25-0.31
STCP	**RA Th R (mm)**	6.3	0.9	0.898	0.000			
	RA Th Ac (mm)	6.7	0.9	0.895	0.000	0.4	0.2	0.33-0.42
TD	**RA Th R (mm)**	5.4	0.6	0.970	0.051			
	RA Th Ac (mm)	6.0	0.6	0.980	0.231	0.5	0.2	0.49-0.57

*Shapiro Wilk ** a negative value indicates that the muscle became thinner in the active state.

As the distribution of almost all parameters were not normal, non-parametric tests were used from this point on.

4.4.2 Correlations between the thicknesses of different muscles when at rest and in a contracted state

Spearman's correlation was performed on the raw scores as the each child's score was compared with their own. As can be seen in (Table 10) below, the Spearman's correlations between the measurements at rest and in the contracted state were all significant ($p < 0.05$) and ranged from *rho* = 0.63 between the TrA at rest and the IO active and 0.96 for the RA at rest and RA contracted. The correlations between the resting and active muscle states ranged from 0.85 (TrA) and 0.96 (RA).

Table 10: Correlations between muscle thicknesses for the entire group (N = 145)

	EO Th R (mm)	IO Th R (mm)	TrA Th R (mm)	RA Th R (mm)	EO Th Ac (mm)	IO Th Ac (mm)	TrA Th Ac (mm)
IO Th R (mm)	0.85						
TrA Th R (mm)	0.86	0.80					
RA Th R (mm)	0.89	0.86	0.84				
EO Th Ac (mm)	***0.85***	0.76	0.65	0.76			
IO Th Ac (mm)	0.74	***0.89***	0.63	0.73	0.81		
TrA Th Ac (mm)	0.76	0.77	***0.86***	0.76	0.75	0.75	
RA Th Ac (mm)	0.86	0.85	0.81	***0.96***	0.79	0.76	0.78

Spearman's *rho*. All correlations significant at a $p < 0.05$ level R denotes at rest and Ac indicates the active state.

4.4.3 Correlation of muscle thickness with age and BMI

As noted above, there was a significant difference in BMI (STCP group was higher) and the children with STCP were almost a year older on average. Although the age difference was not significant, Figure 14 indicated that there were older children in the STCP group. In order to establish if the scoress should be normalized, either according to age or BMI, the correlations between the thickness of each muscle in the contracted and in the active state and BMI and Age were calculated and depicted in (Table 7 above) and (Figure 17 below) shows a scatter plot of age against raw) muscle thickness (non-standardised for both groups (N = 145). Although all correlations were significant, the correlations with BMI were much lower (range = 0.24 - 0.45) compared with the correlations with age in years (range = 0.77 - 0.87) and it was clear that muscle thickness increased with the age of the child. Consequently age was then used to normalise the muscle thickness scores and the normalised scores were then used in further calculations.

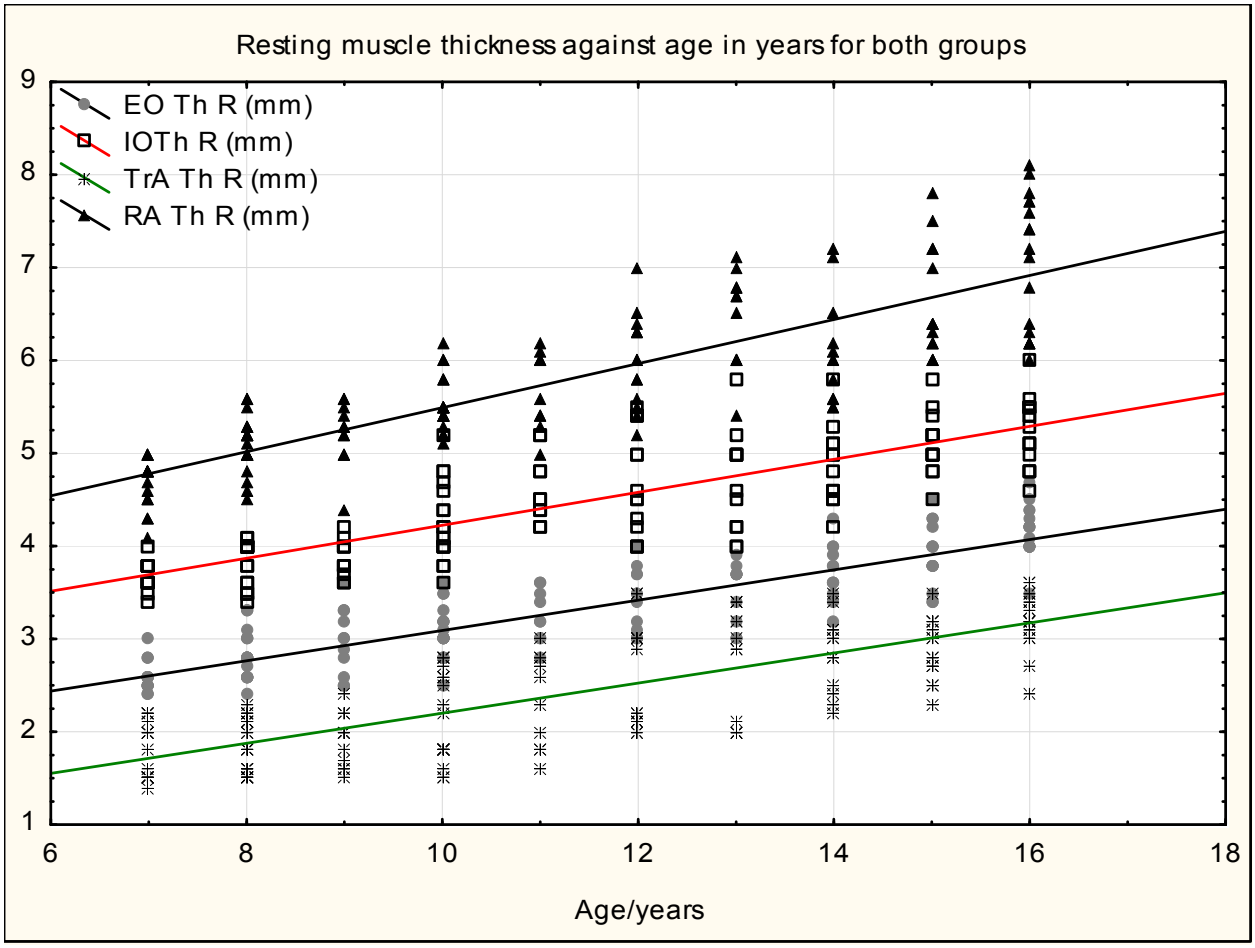


Figure 17: Scatterplot of age against resting muscle thickness for both groups combined (N = 145), raw data / (not normalised for age)

4.4.4 The relationship between resting muscle thickness and age

As shown in Figure 17 above, there is a positive correlation between age and muscle thickness at rest. The order of thickness at rest ranges from RA > IO > EO > TrA.

Table 11: Muscle thickness normalised for age (N = 63 in STCP and N = 82 in TD)

	STCP				TD			
Normalised	**Mean**	**Std.D**	**S Wilks**	**SW p**	**Mean**	**Std.D**	**S Wilks**	**SW p**
Resting values								
EO Th norm R	0.32	0.05	0.92	<0.001	0.23	0.05	0.92	< 0.001
IO Th norm R	0.41	0.06	0.96	0.320	0.40	0.08	0.93	< 0.001
TrA Th nom R	0.25	0.03	0.98	0.268	0.19	0.03	0.92	< 0.001
RA Th norm R	0.55	0.08	0.94	0.005	0.52	0.10	0.93	< 0.001
Active values								
EO Th norm Ac	0.29	0.04	0.94	0.005	0.31	0.06	0.94	< 0.001
IO Th norm Ac	0.38	0.06	0.96	0.030	0.42	0.08	0.93	< 0.001
TrA Th norm Ac	0.22	0.03	0.98	0.238	0.22	0.04	0.95	0.003
RA Th norm Ac	0.58	0.08	0.93	0.002	0.57	0.11	0.93	< 0.001

4.4.5 Muscle thickness normalised for age

Reducing the effect of age by dividing with age did not change the relationship between muscle thickness and age as shown in Table 11 above. The means of the age-normalised thickness showed a significant thickness at rest and on contraction in in all (SWp < 0.001) and SWp = 0.003 for TrA active. As with the raw data, the distributions were not normal and non-parametric statistics were used from this point on as shown in Table 12 below.

Table 12: Muscle thickness normalised for age (N = 63 STCP, N = 82 TD)

	STCP			TD		
	Median	**Minimum**	**Maximum**	**Median**	**Minimum**	**Maximum**
Resting						
EO Th norm R	0.31	0.25	0.43	0.28	0.22	0.37
IO Th norm R	0.41	0.31	0.54	0.40	0.29	0.57
TrA Th norm R	0.25	0.19	0.31	0.19	0.15	0.30
RA Th norm R	0.54	0.43	0.71	0.51	0.38	0.71
Active						
EO Th norm Ac	0.28	0.23	0.43	0.30	0.23	0.43
IO Th norm Ac	0.38	0.30	0.50	0.41	0.31	0.60
TrA Th norm Ac	0.22	0.17	0.29	0.22	0.16	0.33
RA Th norm Ac	0.57	0.46	0.77	0.56	0.41	0.77

4.4.6 Medians of muscle thickness normalised for age

The relative thicknesses of the muscles in the two groups did not alter as the medians of the normalized data (Table 12 above) similarly indicated that RA was the thickest muscle, followed by IO, EO and then TrA. The median of the thickness of all the muscles was greater at rest in the STCP group, but the picture was less clear in the active state with EO and IO being thicker and RA being thinner (statistical comparison done below).

4.4.7 Comparison of the muscle thickness between the two groups

The resting and active normalised thickness of the muscle groups were compared (Table 13 below). In the resting state, EO and TrA were significantly thicker in the STCP and on contraction IO was thicker in the TD group. Although the median of RA was lower in the STCP group, the rank ordering was significantly higher in the TD group as shown in (Table 13 below).

Table 13: Comparison of Mann-Whitney rank sum for resting and active states thickness of all muscles between the two groups (normalised for age). (STCP: N = 63; TD: N = 82)

	Rank Sum - STCP	Rank Sum – TD	U	Z - adjusted	p-value
Resting					
EO Th norm R	5494	5091	1688	3.6	**< 0.001**
IO Th norm R	4913	5672	2269	1.3	0.211
TrA Th norm R	6550	4035	632	7.8	**< 0.001**
RA Th norm R	5143	5443	2040	2.2	**0.030**
Active					
EO Th norm Ac	4152	6434	2136	-1.8	0.074
IO Th norm Ac	3927	6658	1911	-2.7	**0.007**
TrA Th norm Ac	4618	5968	2565	0.1	0.943
RA Th norm Ac	4873	5712	2309	1.1	0.275

4.4.8 Change in age-normalised muscle thickness from resting to active state

The difference between the normalised resting and active states were calculated (Table 14). The medians scores show a decrease for the EO, IO and TrA in the STCP group whereas the RA showed a positive change from the resting to the active state. The median scores for the TD group showed positive results.

Table 14: Median values of the change in muscle thickness in the normalised scores between resting and active state in the two groups (STCP: N = 63, TD: N = 82)

	STCP			TD		
	Median	**Minimum**	**Maximum**	**Median**	**Minimum**	**Maximum**
EO Th dif norm	-0.02	-0.07	0.01	0.02	-0.01	0.06
IO Th dif norm	-0.03	-0.11	0.02	0.02	0.00	0.09
TrA Th dif norm	-0.03	-0.06	0.00	0.03	-0.01	0.07
RA Th dif norm	0.03	0.01	0.09	0.05	-0.02	0.09

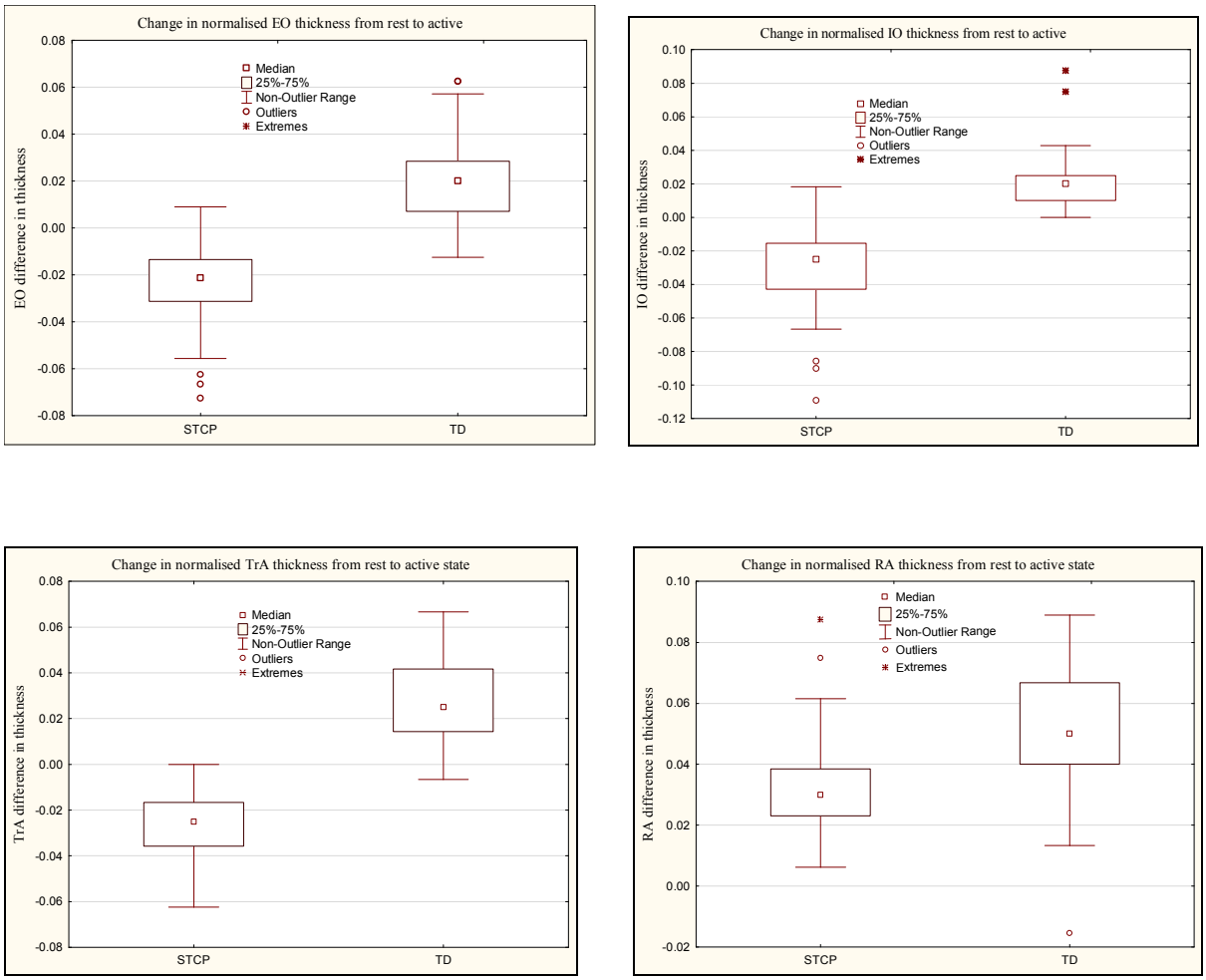


Figure 18: Comparison of change in muscle thickness from rest to contraction for all four muscles in the two groups (STCP: N = 63; TD: N = 82)

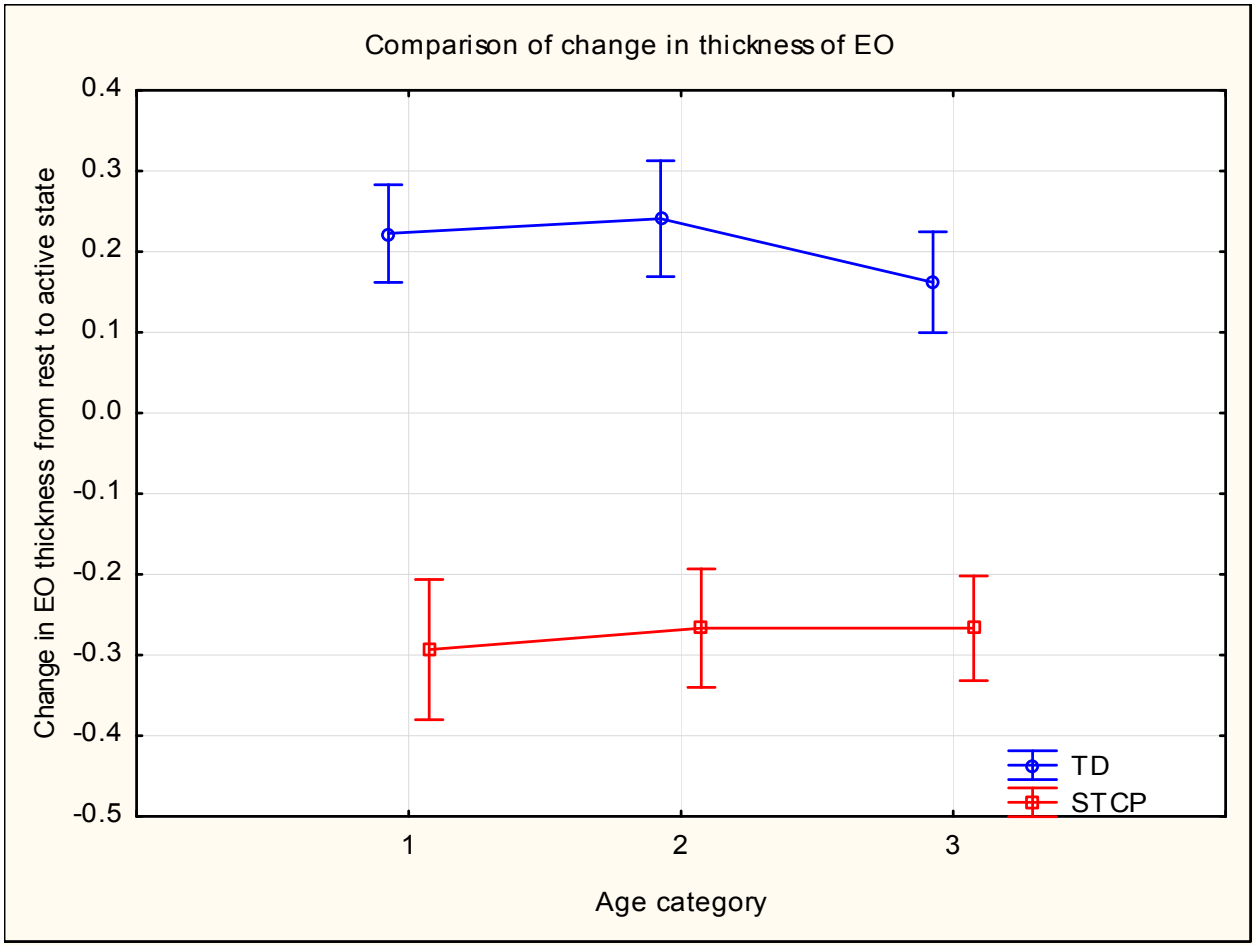


Figure 19: Graphical representation of changes in EO thickness from resting to active state against categorised ages in years for both groups

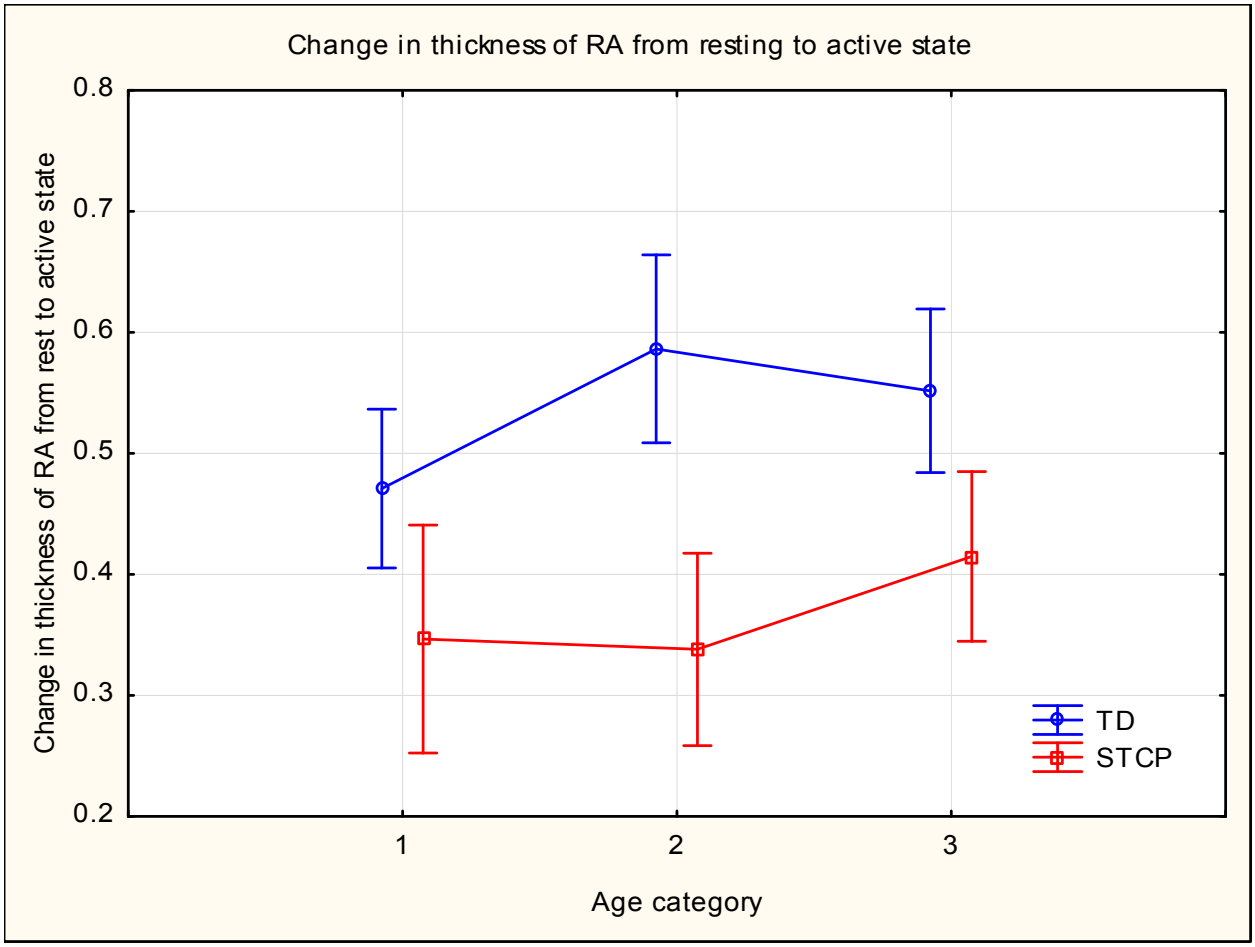


Figure 20: Graphical representation of changes in RA thickness from resting to active state against categorised ages in years for both groups

4.4.9 Changes in muscles thickness from rest to active amongst age categories

The age groups of the children were categorized as one = seven to nine–years, two = ten- to twelve-years and three = thirteen to sixteen-years and the changes in thickness and EMG from rest to activity were compared between TD and STCP children at each age. In each case the EO, IO and TrA showed less change from rest to activity and decreased in thickness as shown in Figure 19 above. (NB: The plot of changes in EO thickness against age represents the typical changes observed in the three anterolateral abdominal muscles - EO, IO & TrA). The age of the children did not influence the amount of change as can be seen by the overlap in the 95% CIs of each age.

As noted before, the difference between RA in the TD and children with STCP was less marked and in the younger and older age groups, the 95% CIs overlapped as shown in Figure 20 above.

4.4.10 Comparison of rank sum of the change in muscle thickness from resting to active states for all muscles between the two groups (STCP: N = 63; TD: N = 82)

As shown in (Table 15 below), the muscles of the TD children all showed a greater change in thickness from rest to the active state. For EO, IO and TrA in the STCP group, all measurements of muscle thickness decreased as shown from the Mann-Whitney rank sums, but not for RA. The test results also indicate that the amount of change was significantly greater in the TD group for each muscle ($p < 0.001$).

Table 15: Comparison of rank sum of the difference between resting and active states for all muscles between the two groups

	Rank Sum – STCP	Rank Sum – TD	U		Z – adjusted	p-value
EO Th dif norm	2074	8512	58		-10.1	**< 0.001**
IO Th dif norm	2086	8499	70		-10.0	**< 0.001**
TrA Th dif norm	2021	8565	5		-10.3	**< 0.001**
RA Th dif norm	3108	7478	1092		-5.9	**< 0.001**

4.5 Muscle parameters – pennation angle (PA)

A similar process of analysis as that applied to muscle thickness was used to analyse the PA data. Once again age was found to be highly correlated with PA and age-normalised scores were calculated and used for the analyses. Note that there are no values for the pennation angle and for muscle fibre length for RA as the muscle was found to have a numerical PA value of zero, therefore only muscle thickness was recorded and analysed for RA in both groups.

4.5.1 Descriptive statistics for PA between the two groups (STCP: N = 63, TD: N = 82)

The raw PA scores for the two groups were presented in Table 16 below. The PA of all of these muscles in both groups during the resting and active states was less than three degrees The PA decreased in the STCP group from rest to active state while it increased in the

children from the TD group from rest to active state in all the three muscles (EO, IO & TrA). The standard deviations for all three sets of muscles in both groups were shown to be within narrow ranges.

Table 16: Pennation angle raw scores at rest and in the contracted state, tests for normality and the difference between the resting and contracted states (STCP: N = 63, TD: N = 82)

		Mean	SD.	SW	P value	Difference between resting and active	SD of difference	95% CI of difference
STCP	**EO PA R**	1.9	0.26	0.961	0.042			
	EO PA Ac	1.8	0.21	0.942	0.005	-0.05	0.16	-0.09-(-0.01)
TD	**EO PA R**	1.6	0.20	0.963	0.054			
	EO PA Ac	1.9	0.25	0.939	0.004	0.27	0.23	0.22-0.32
STCP	**IO PA R**	2.1	0.23	0.874	< 0.001			
	IO PA Ac (mm)	2.0	0.22	0.945	< 0.007	-0.1	0.14	-0.13-(0.07)
TD	**IO PA R**	1.9	0.20	0.884	< 0.001			
	IO PA Ac (mm)	2.1	0.18	0.946	0.002	0.18	0.11	0.15-0.20
STCP	**TrA PA R**	1.6	0.21	0.903	< 0.001			
	TrA PA Ac	1.5	0.22	0.931	< 0.001	-0.06	0.16	-0.1-(-0.02)
TD	**TrA PA R**	1.2	0.30	0.925	< 0.001			
	TrA PA Ac	1.4	0.32	0.958	0.010	0.18	0.17	0.14-0.21

SW = Shapiro Wilk

4.5.2 Correlations between the PA and the individual muscles during the resting and active states for both groups (STCP: N = 145)

Figure 17 below indicates that the ranking of all the scores correlated positively between muscles at (rest *rho* = 0.55 IO resting and TrA resting to 0.74 for EO and TrA resting). No

correlation was seen between the resting and active states for any of the muscles *rho* = 0.18 to 0.30. Only the PA of EO and IO correlated fairly during the active state *(rho* = 0.65), while PA of TrA showed no correlation with any of the muscles during the contracted state (*rho* = 0.32 and 0.37).

Table 17: Spearman's correlations between the pennation angles of the different muscles in their resting and active states. (N = 145)

	EO PA R	IO PA R	TrA PA R	EO PA Ac	IO PA Ac
IO PA R	0.59				
TrA PA R	0.74	0.55			
EO PA Ac	***0.45***	0.46	0.23		
IO PA Ac	0.30	***0.64***	0.18	0.65	
TrA PA Ac	0.66	0.56	***0.77***	0.32	0.37

Spearman's *rho,* All correlations significant at a $p < 0.05$ level

4.5.3 Correlation of PA with age and BMI

The results of Spearman correlation test between the pennation angle and age as well as for PA and BMI indicated that the pennation angles were highly significantly correlated with age and to a lesser extent with BMI Table 18 below. Consequently, the data were normalised for age.

Table 18: Correlation of pennation angle with Age and BMI

	Age/years	BMI
EO PA R	0.65	0.36*
IO PA R	0.68	0.28*
TrA PA R	0.66	0.39*
EO PA Ac	0.46	0.13
IO PA Ac	0.59	0.06
TrA PA Ac	0.77	0.41*

All correlations with age were significant at $p < 0.001$ level or at a $p < 0.05$ level (those marked with *).

4.5.4 Pennation angles normalised for age

As with the raw data, the normalised pennation angles were not normally distributed Table 19 and from this point on non-parametric statistics were used for analysis.

Table 19: Pennation angles normalised for age (N = 63 in STCP and N = 82 in TD)

	STCP				TD			
	Mean	**Std. D**	**Shapiro Wilks**	**p value**	**Mean**	**Std. D**	**Shapiro Wilks**	**p value**
EO PA norm R	0.17	0.04	0.925	< 0.001	0.15	0.03	0.916	< 0.001
IO PA norm R	0.19	0.04	0.942	0.006	0.19	0.04	0.939	< 0.001
TrA PA norm R	0.14	0.03	0.927	0.001	0.11	0.02	0.945	0.002
EO PA norm Ac	0.16	0.04	0.925	< 0.001	0.18	0.04	0.928	< 0.001
IO PA norm Ac	0.18	0.04	0.937	0.003	0.20	0.05	0.940	< 0.001
TrA PA norm Ac	0.13	0.02	0.964	0.059	0.13	0.02	0.945	0.002

The medians and ranges of the normalised pennation angles indicate that the pennation angles of IO at rest and in the active state were the greatest in both groups Table 20.

Table 20: Medians of pennation angles normalised for age (N = 63 STCP and N = 82 TD)

	STCP			TD		
	Median	**Min**	**Max**	**Median**	**Min**	**Max**
Resting						
EO PA norm R	0.16	0.11	0.26	0.15	0.11	0.23
IO PA norm R	0.18	0.13	0.29	0.18	0.11	0.28
TrA PA norm R	0.13	0.10	0.23	0.11	0.07	0.16
Active						
EO PA norm Ac	0.15	0.11	0.29	0.17	0.11	0.27
IO PA norm Ac	0.17	0.12	0.26	0.20	0.13	0.31
TrA PA norm Ac	0.13	0.09	0.20	0.12	0.08	0.19

As already stated, generally PA decreased in STCP cases from rest to active states and increased in the TD as indicated by median scores in the Table 20 above.

4.5.5 Comparison of the normalised pennation angle between the two groups (STCP: N = 63, TD: N = 82)

The results of the comparison between age-normalised resting and active pennation angles are presented in Table 21. The ranking of the pennation angles of the TrA at rest were significantly greater in the STCP, whereas the ranking of the pennation angles of the EO and IO in the TD group during the active state were significantly greater.

Table 21: Comparison of Mann-Whitney rank sum for resting and active pennation angles of all muscles between the two groups (normalised for age). (STCP = 63, TD = 82)

	Rank Sum – STCP	Rank Sum – TD	U	Z – adjusted	p-value
EO PA norm R	5005	5580	2177	-1.62	0.105
IO PA norm R	4636	5950	2547	-0.14	0.886
TrA PA norm R	6215	4370	967	-6.45	***< 0. 001***
EO PA norm Ac	3910	6676	1894	2.75	***0.006***
IO PA norm Ac	3775	6811	1759	3.29	***0.001***
TrA PA Ac norm	5108	5477	2074	-2.03	***0.042***

As can be seen in the graphical representation of the normalised pennation angles during the active state in Figure 21, TrA showed a smaller pennation angle on contraction in the TD group.

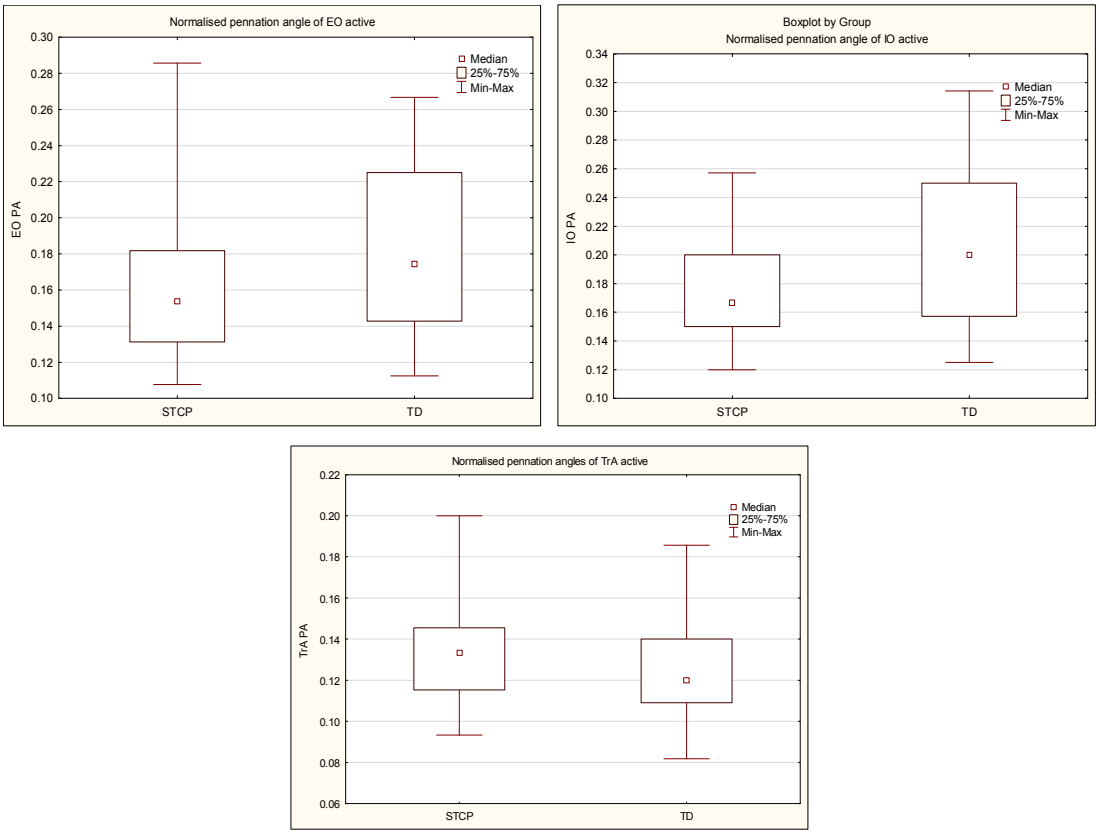


Figure 21: Comparison between the PA angles of the STCP and TD group in the active state. (STCP: N = 63, TD:N = 82)

4.5.6 Change in pennation angle from rest to active state

The change in the age- normalised pennation angles from the resting to the active state were calculated and the results shown in Table 22 below. The results of the median scores are similar between the two groups Table 22. The TD children had a greater change, with the pennation angle increasing on contraction. In contrast individuals in the STCP showed a decrease or no change in pennation angle. From Table 23 below, a significant difference between the STCP and TD groups is shown in the Mann-Whitney rank sums ($p < 0.001$).

Table 22: Change in normalised pennation angle from resting to active state in both groups (N = 145)

	STCP				TD			
	N	**Median**	**Min**	**Max**	**N**	**Median**	**Min**	**Max**
EO dif PA norm	63	0.00	-0.04	0.05	82	0.02	0.00	0.11
IO dif PA norm	63	-0.01	-0.06	0.05	82	0.02	-0.02	0.09
TrA dif PA norm	63	0.00	-0.06	0.03	82	0.01	-0.02	0.08

Table 23: Comparison of the Mann-Whitney rank sum for the change in pennation angle from resting to active state (STCP: N = 63, TD: N = 82)

	Rank Sum – STCP	**Rank Sum – TD**	**U**	**Z - adjusted**	**p-value**
EO dif PA	2594	7992	577.5	8.046	**< 0.001**
IO dif PA	2256	8329	240.0	9.384	**< 0.001**
TrA dif PA	2766	7820	749.5	7.345	**< 0.001**

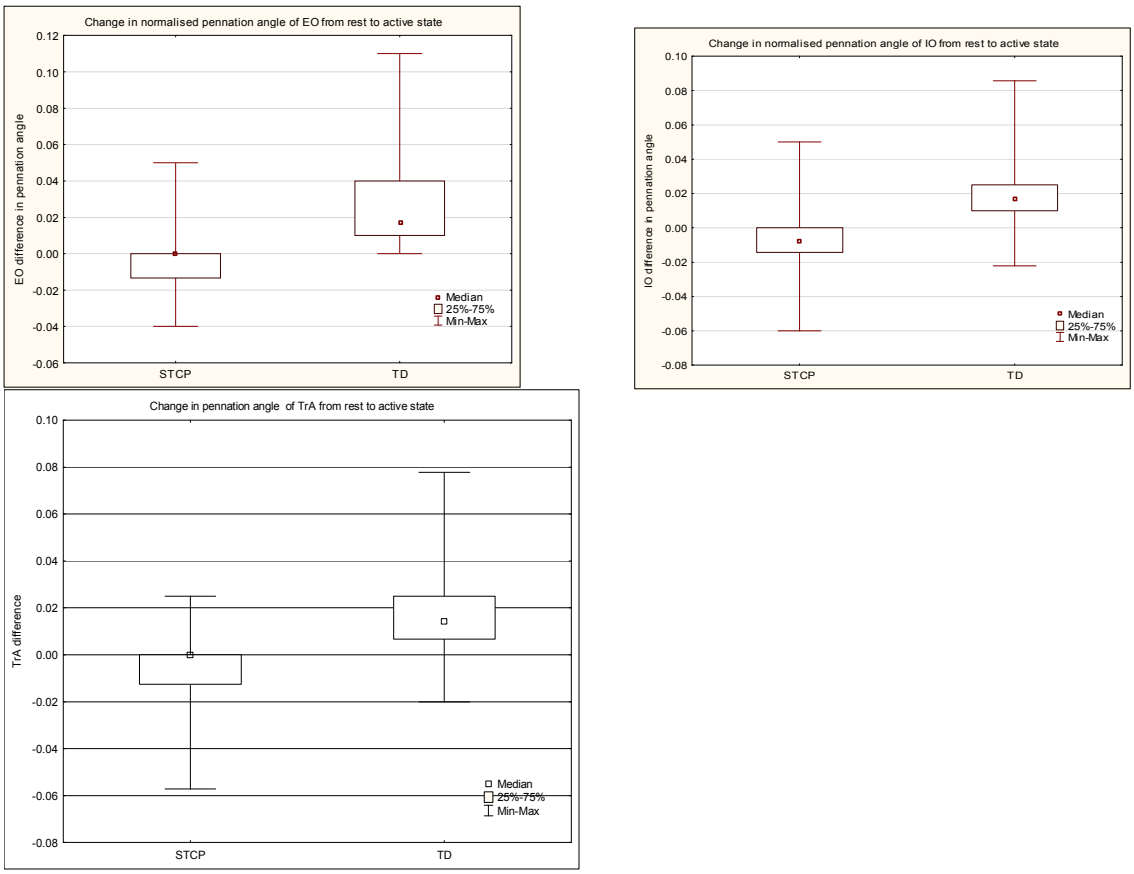


Figure 22: Comparison of change in pennation angle from resting to active state between the two groups (STCP: N = 63, TD: N = 82)

4.6 Muscle parameters – fibre length

4.6.1 Raw data: fibre length

The results of the descriptive statistics for fibre length in the two groups Table 24 showed that the fibre length in children decreased from rest to the active state in all muscles in both groups of children, apart from TrA in the TD group (95% CI = -2.1 to 3.3, p = 0.038). The fibre lengths were generally longest in IO, followed by EO and then TrA. In every case they decreased from the resting to the active state, although the change in TrA was small in the TD group.

Table 24: Resting and active fibre length scores, tests for normality and the difference between the resting and contracted states (STCP: N = 63; TD: N = 82) [see overleaf]

		Mean	SD.	SW*	P value	Difference between resting and active	SD of difference	95% CI of difference
STCP	**EO FL R (mm)**	112.2	14.6	0.96	0.025			
	EO FL Ac (mm)	106	15.6	0.96	0.031	6.2	12.2	3.1-9.2
TD	**EO FL R (mm)**	108.5	10.2	0.96	0.018			
	EO FL Ac (mm)	99.6	11.7	0.98	0.237	8.8	11.8	6.3-11.4
STCP	**IO FL R (mm)**	129.7	13.4	0.98	0.381			
	IO FL Ac (mm)	126.7	16.1	0.98	0.403	3.0	11.3	0.2-5.9
TD	**IO FL R (mm)**	126.4	12.7	0.97	0.030			
	IO FL Ac (mm)	121.2	11.4	0.95	0.003	5.1	7.3	3.5-6.8
STCP	**TrA FL R (mm)**	103.8	16.3	0.96	0.068			
	TrA FL Ac (mm)	96.2	12.8	0.96	0.033	7.6	11.9	4.6-10.6
TD	**TrA FL R (mm)**	103.4	13.6	0.97	0.038			
	TrA FL Ac (mm)	102.8	15.3	0.97	0.038	0.6	12.2	-2.1-3.3

*Shapiro Wilk

4.6.2 Correlations between the fibre length at rest and in contracted state

Spearman's correlation was performed on the raw scores as the each child's score was compared with their own. Intra-muscle correlation between the resting and active states ranged from *rho* = 0.53 (EO) to *rh*o = 0.75 (IO).

Table 25: Spearman's correlation between the fibre length of all the muscles at the resting and active states for both groups (N = 145)

	EO FL R (mm)	IO FL R (mm)	TrA FL R (mm)	EO FL Ac (mm)	IO FL Ac (mm)
IO FL R (mm)	0.26				
TrA FL R (mm)	0.27	0.19			
EO FL Ac (mm)	***0.53***	0.46	0.23		
IO FL Ac (mm)	0.33	***0.75***	0.17	0.54	
TrA FL Ac (mm)	0.03	-0.05	***0.63***	0.02	-0.05

Spearman's *rho,* All correlations significant at a $p < 0.05$ level

4.6.3 Correlation of fibre length with Age and BMI

The relationship between age and BMI was determined using the Spearman's correlation test and the results obtained were presented in Table 26 below. All correlations were significant at $p < 0.005$; the correlation with age was significantly greater than with BMI, therefore fibre length was also standardised with age.

Table 26: Correlation of muscle fibre length (raw data) with Age (years) and BMI (kgm-2) (N = 145)

	Age/years	BMI
Resting		
EO FL R (mm)	0.54**	0.26*
IO FL R (mm)	0.42**	0.20*
TrA FL R (mm)	0.28*	-0.002
Active		
EO FL Ac (mm)	0.58**	0.18*
IO FL Ac (mm)	0.48**	0.22*
TrA FL Ac (mm)	0.06	-0.26*

**p < 0.01, *p < 0.05

The results from Table 26 above shows no correlation between fibre length and BMI, (*rho* = -002 to 0.26). Age and fibre length showed a slightly positive correlation (*rho* = 0.42 to 0.58 for EO and IO). Although the TrA active was not correlated with age (*rho* = – 0.002 TrA resting and *rho* = -0.26 TrA active), it would have been difficult to compare this value with the others if it had not been normalised. The fibre lengths were subsequently normalised for age.

4.6.4 Comparison of the fibre lengths between the two groups

A comparison between the rankings of the normalised fibre lengths (Table 27 below) indicated that there was no significant difference between the resting lengths of the two groups with the exception of TrA in the active state. However, in every muscle the fibre length was ranked higher (longer) in the TD group.

Table 27: Comparison of resting and active muscle fibre lengths of all muscles between the two groups (normalised for age) (STCP: N = 63, TD: N = 82)

	Rank Sum – STCP	Rank Sum - TD	U	Z - adjusted	p-value
Resting					
EO FL norm R	4305	6280	2289	-1.17	0.242
IO FL norm R	4362	6223	2346	-0.94	0.345
TrA FL norm R	4214	6371	2198	-1.53	0.125
Active					
EO FL norm Ac	4497	6088	2481	-0.40	0.686
IO FL norm Ac	4441	6144	2425	-0.63	0.530
TrA FL norm Ac	3947	6638	1931	-2.60	0.009

4.6.5 Change in fibre length from rest to active state (STCP: N = 63, TD: N = 82)

The changes in age-normalised fibre length from rest to active states for the STCP and TD groups were tested with a Mann-Whitney rank sum statistic and the results shown in Table 28 below. A statistically significant difference was observed in TrA normalised data with the STCP showing a greater decrease in fibre length.

Table 28: Comparison of the Mann-Whitney rank sum for the change in normalised muscle fibre length from resting to active state (STCP: N = 63, TD: N = 82)

	Rank Sum – STCP	Rank Sum - TD	Z – adjusted	p-value
EO FL dif norm	4864	5721	1.06	0.291
IO dif FL norm	4171	6414	-1.71	0.088
TrA dif FL norm	5430	5155	3.31	0.001

4.7 EMG Parameters

4.7.1 Raw data: EMG

The raw scores of the EMG for the different muscles groups are depicted in Table 29

below. In every case the EMG increases considerably on contraction. The change in EMG activity from rest to active is lowest in EO & IO greatest for RA in the STCP group (95% CI = 37.0 to 38.6 and 84.8 to 85.4 respectively). The data are not normally distributed therefore non-parametric tests were used.

Table 29: Descriptive statistics for EMG raw scores

		Mean	SD	SW*	P value	Difference between resting and active	SD of difference	95% CI of difference
STCP	**EO R EMG (Hz)**	85	2.3	0.93	0.002			
	EO Ac EMG (Hz)	123.1	2.5	0.81	< 0.001	38.1	2.1	37.6-38.6-
TD	**EO R EMG (Hz)**	11.8	1.6	0.88	< 0.001			
	EO Ac EMG (Hz)	107.3	1.8	0.79	< 0.001	95.5	1.5	95.1-98.0
STCP	**IO R EMG (Hz)**	89.9	4	0.91	< 0.001			
	IO Ac EMG (Hz)	127.5	3.8	0.83	< 0.001	37.7	2.8	37.0-38.4
TD	**IO R EMG (Hz)**	11.6	1.6	0.84	< 0.001			
	IO Ac EMG (Hz)	110.8	2	0.80	< 0.001	99.2	1.7	98.6- 99.8
STCP	**RA R EMG (Hz)**	12.2	1.4	0.91	< 0.001			
	RA Ac EMG (Hz)	97.3	1.8	0.90	< 0.001	85.1	1.2	84.8-85.4
TD	**RA R EMG (Hz)**	11.4	1.4	0.84	< 0.001			
	RA Ac EMG (Hz)	97	1.8	0.91	< 0.001	85.6	1.3	85.3-88.3

*SW = Shapiro Wilks

4.7.2 Correlation of EMG with age and BMI

The relationship between EMG and age was not as strong as it was for the other parameters (refer to Table 30 below) and for some subjects the relationship between EMG and BMI was stronger. However, when the two groups were analysed separately, age had generally a much stronger negative relationship with EMG. A negative relationship between BMI and EMG

also emerged, which was stronger in the TD group than for the children with STCP as shown in Table 31 below.

Table 30: Correlation of raw EMG score with Age and BMI (N = 145)

	Age in years (*rho*)	**BMI (Kg.m^{-2}) (*rho*)**
Resting values		
EO R EMG (Hz)	-0.27*	0.16
IO R EMG (Hz)	-0.28*	0.16
RA R EMG (Hz)	-0.67*	-0.08
Active values		
EO Ac EMG (Hz	-0.16	0.19**
RA Ac EMG (Hz	-0.16	0.18**
IO Ac EMG (Hz)	-0.70*	-0.21**

*Significant at $p < 0.001$ level. ** Significant at $p < 0.05$ level.

Table 31: Spearman's rho correlations of EMG (Hz) with age and BMI for both groups separately (STCP = 63, TD = 82)

	STCP - 63		TD – 82	
Resting - Age	**Spearman**	**p-value**	**Spearman**	**p-value**
EO R EMG FREQ (Hz)	-0.71	**p < 0.001**	-0.84	**p < 0.001**
IO R EMG FREQ (Hz)	-0.73	**p < 0.001**	-0.88	**p < 0.001**
RA R EMG FREQ (Hz)	-0.61	**p < 0.001**	-0.89	**p < 0.001**
Active - Age				
EO Ac EMG FREQ (Hz)	-0.26	**0.036**	-0.76	**p < 0.001**
IO Ac EMG FREQ (Hz)	-0.32	**0.012**	-0.74	**p < 0.001**
RA Ac EMG FREQ (Hz)	-0.64	**p < 0.001**	-0.81	**p < 0.001**
Resting - BMI				
BMI & EO R EMG FREQ (Hz)	-0.04	0.764	-0.36	**0.001**
BMI & IO R EMG FREQ (Hz)	-0.06	0.653	-0.36	**0.001**
BMI & RA R EMG FREQ (Hz)	0.00	0.974	-0.31	**0.004**
Active - BMI				
BMI & EO Ac EMG FREQ (Hz)	-0.11	0.400	-0.27	**0.015**
BMI & IO Ac EMG FREQ (Hz)	-0.03	0.793	-0.34	**0.002**
BMI & RA Ac EMG FREQ (Hz)	-0.07	0.578	-0.39	**p < 0.001**

4.7.3 Correlations of EMG with age and BMI for both groups separately (STCP = 63, TD = 82)

As age was observed to have a strong negative correlation, the EMG scores were subsequently divided by the age of the participant for standardisation. The descriptive statistics for the age-normalised EMG score for both groups, and the change in age-normalised EMG activity were presented in Table 32 below.

Table 32: Descriptive Statistics for normalised EMG score for the two groups (STCP: N = 63; TD: N = 82)

	STCP			TD		
	Median	**Min**	**Max**	**Median**	**Min**	**Max**
Resting						
EO EMG norm R	7.2	5.1	12.6	1.1	0.6	2.1
IO EMG norm R	7.7	5.3	13.6	1.1	0.6	2.1
RA EMG norm R	1.1	0.6	2.1	1.1	0.6	2.1
Active						
EO EMG norm Ac	10.4	7.5	17.7	10.6	6.4	15.7
IO EMG norm Ac	10.8	7.7	18.6	11.0	6.6	16.4
RA EMG norm Ac	8.1	5.9	14.1	9.6	5.9	14.4
Difference in normalised score						
EO EMG norm dif	3.3	2.2	5.1	9.4	5.7	13.9
IO EMG norm dif	3.2	2.3	5.1	9.8	6.0	14.4
RA EMG norm dif	7.1	5.3	12.3	8.4	5.3	12.7

4.7.4 Descriptive Statistics for normalised EMG score for the two groups (STCP: N = 63; TD: N = 82)

The normalised score for EMG scores and the changes in EMG activity between resting and active states were presented in Table 32 above. The t-test showed differences in the resting EMG of the STCP and TD group. The median scores at rest for the EO and IO are higher (7.2 and 7.7) than the RA (median = 1.1) in the STCP group. The EMG activity for EO and IO in the STCP group at rest is higher than the TD group (median 1.1). The EMG activity of RA at rest in both groups is similar (median = 1.1).

Results also show differences in the changes in EMG activity from rest to active states in the EO and IO muscles for the STCP and the TD group (median = 3.2 to 3.3 and 9.4 to 9.8 respectively). The changes in the EMG activity for RA in both groups are comparable (median = 7.1 and 8.4) for STCP and TD respectively.

4.7.5 Correlation between the EMG of different muscles at rest and in the contracted state for the STCP group (N = 63)

Table 33 below shows results of Spearman's *rho* between the EMG activity of the various muscles at rest and in the active state for the STCP group. EMG activity for all the muscles are highly correlated when relaxed (*rho* = 0.75 to 0.93). There is no correlation between the resting and active EMG activity among the muscles (*rho* = 0.11 to 0.19). The EO and IO are the most correlated during the active states *(rho* = 0.92). The correlation for RA and the other muscles is lowest during the active state (*rho* = 0.46 and 0.49) between it and respectively for the EO and IO.

Table 33: Spearman's correlation between the EMG of different muscles at rest and in the contracted state for the STCP group (N = 63)

	EO R EMG FREQ (Hz)	IO R EMG FREQ (Hz)	RA R EMG FREQ (Hz)	EO Ac EMG FREQ (Hz)	IO Ac EMG FREQ (Hz)
IO R EMG FREQ (Hz)	0.93				
RA R EMG FREQ (Hz)	0.77	0.75			
EO Ac EMG FREQ (Hz)	0.11	0.17	-0.04		
IO Ac EMG FREQ (Hz)	0.12	0.16	-0.05	0.92	
RA Ac EMG FREQ (Hz)	0.16	0.19	0.08	0.45	0.49

4.7.6 Correlation between the EMG of different muscles at rest and in the contracted state for the TD group (N = 82)

The results in Table 34 below shows the Spearman's rho correlation among the individual muscles in the TD group. All the muscles are highly correlated during when at rest (*rho* = 0.84 to 0.90). No correlation shown amongst muscles between the resting and contracted state, (*rho* = -0.31 to -0.07). The lowest correlation amongst muscles on contraction existed between the RA (*rho* = 0.46 and 0.49) and EO & IO respectively. The oblique muscles show strong correlation during the active state (*rho* = 0.93).

Table 34: Spearman's correlation between the EMG of different muscles at rest and in the contracted state for the TD group (N = 82)

	EO R EMG FREQ (Hz)	IO R EMG FREQ (Hz)	RA R EMG FREQ (Hz)	EO Ac EMG FREQ (Hz)	IO Ac EMG FREQ (Hz)
IO R EMG FREQ (Hz)	0.90				
RA R EMG FREQ (Hz)	0.84	0.87			
EO Ac EMG FREQ (Hz)	-0.11	-0.07	-0.08		
IO Ac EMG FREQ (Hz)	-0.12	-0.08	-0.06	0.93	
RA Ac EMG FREQ (Hz)	-0.31	-0.22	-0.20	0.46	0.49

4.7.7 Correlation between normalised EMG activity and change in muscle thickness

The Spearman's correlation results in Table 35 above shows no association between changes in normalised EMG activity and muscle thickness from the resting to the active state in the STCP group. A weak but significantly positive correlations ($p = 0.008$) were recorded for the RA in the STCP group similar to the correlations shown in the TD group.

Table 35: Spearman's Rank Correlation between changes in normalised in EMG activity and changes in normalised muscle thickness from rest to active states

	STCP *rho*	t(N-2)	p-value	TD *rho*	t(N-2)	p-value
EO dif norm & EMG EO Th dif norm	-0.386	-3.27	0.002	0.517	5.405	$p < 0.001$
IO dif norm & EMG IO Th dif norm	-0.199	-1.59	0.117	0.516	5.382	$p < 0.001$
RA dif norm & EMG RA Th dif norm	0.329	2.72	0.008	0.510	5.297	$p < 0.001$

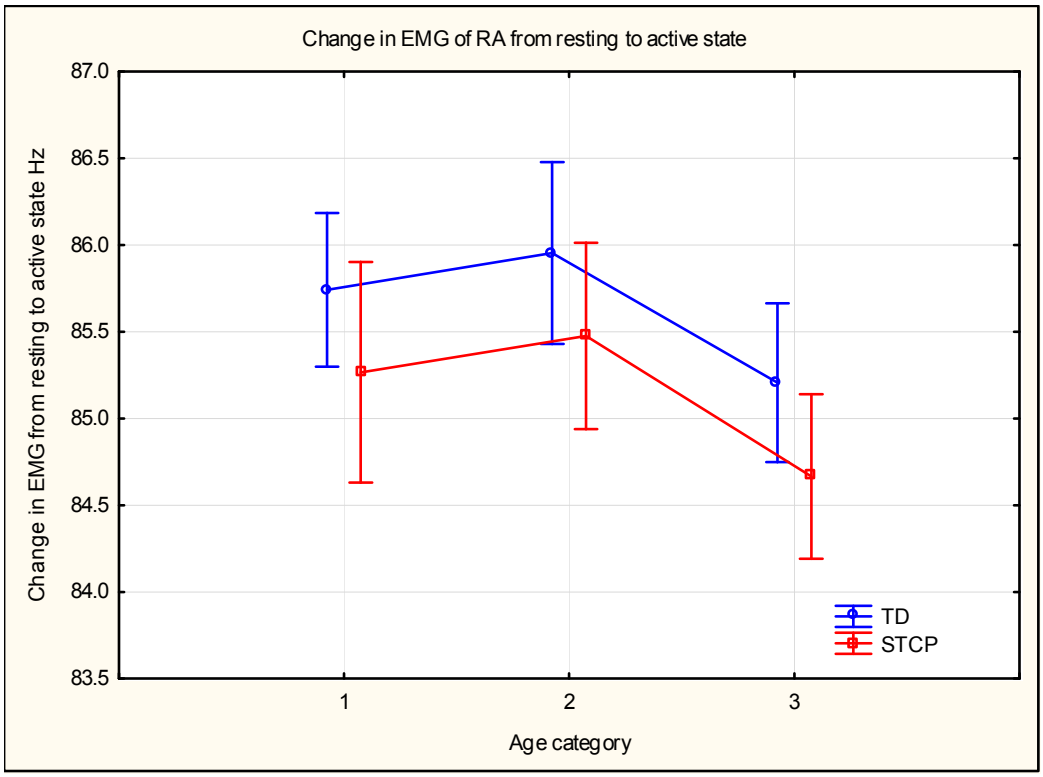


Figure 23: Graphical representation of changes in RA thickness from resting to active state against categorised ages in years for both groups (N = 145).
Key: 1 = 7 – 9 years; 2 = 10 – 12 years and 3 = 13 – 16 years.

4.7.8 Correlation between EMG activity and age categories for the two groups (N = 145)

With regard to the changes in EMG activity, there was overlap between each age category and between the two groups as shown in (Figure 23 above). It can be concluded that the action of RA is similar at each age between the two groups. However, the actions of EO, IO and TrA are consistently different at each age. There is no evidence that the children with STCP demonstrate more primitive patterns and are delayed in the development of abdominal muscle control. Rather, the patterns of muscle recruitment are abnormal at each age and remain so.

4.8 Functional parameters

4.8.1 Scores for the gross motor function measure (GMFM)

As the GMFM is an ordinal scale, non-parametric statistics were used. The median score was 58 with a range of 28 - 86. A histogram of the scores is given in Figure 24 below.

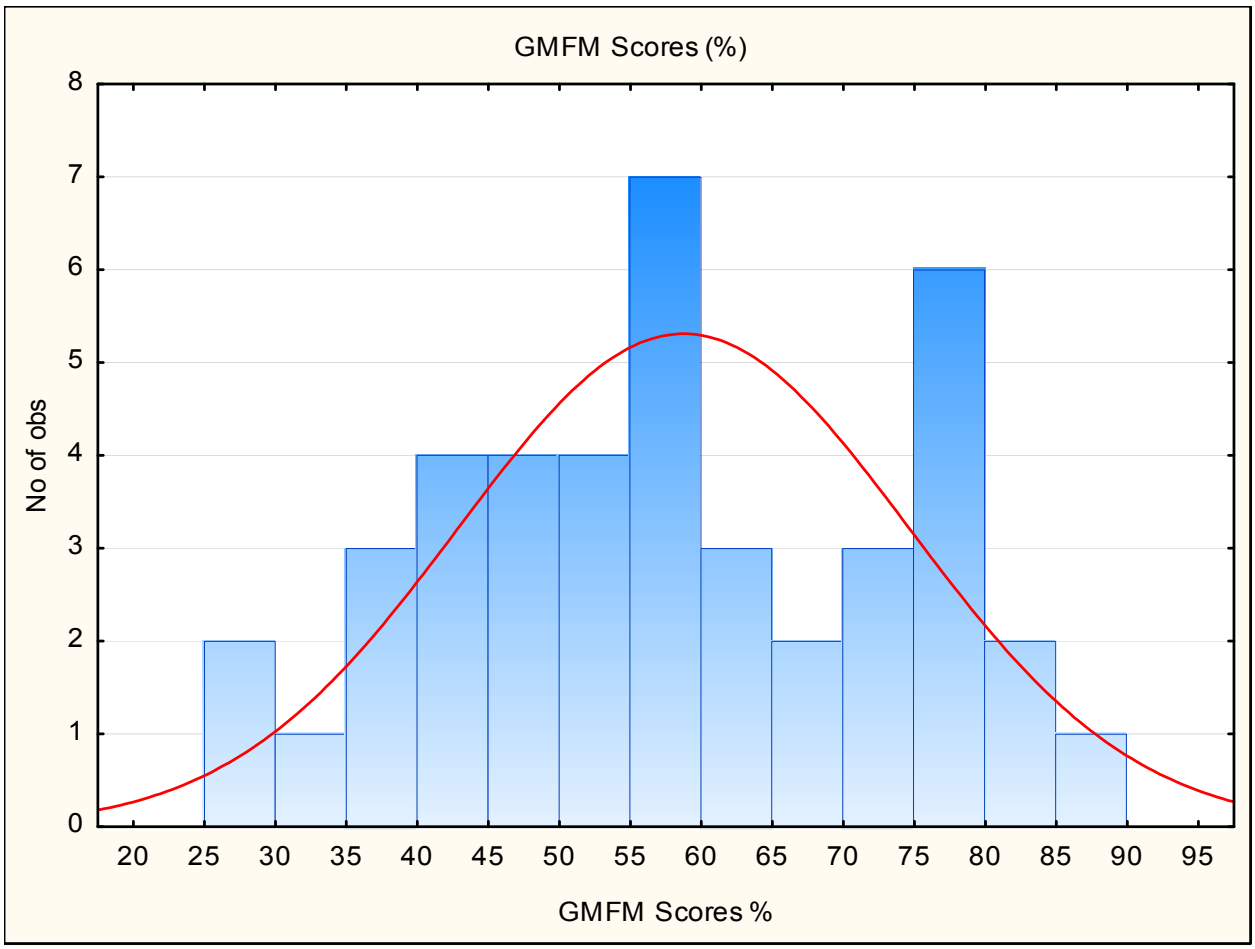


Figure 24: Histogram of the GMFM scores (N = 42)

4.8.2 Relationship between the GMFM scores for each of the GMFCS (disability) levels

As can be seen in (Table 36 below) the GMFM scores decreased as the GMFCS level increased (i.e. as child became more disabled). There was a significant difference in the rank ordering of each level (Kruskall-Wallis H (3, N= 42) = 35.17; p > 0.001). Post-hoc analysis indicated that the differences lay between levels at least one level apart (e.g. between I and III, and IV). This relationship is shown graphically by the box and whiskers plots in Figure 25 below.

Table 36: Differences between the GMFM scores for each of the GMFCS levels

Level	1 - :36.955	2 - R:25.150	3 - R:16.273	4 - R:6.6000
1		0.166	0.000	0.000
2	0.166		0.586	0.004
3	0.000	0.586		0.427
4	0.000	0.004	0.427	

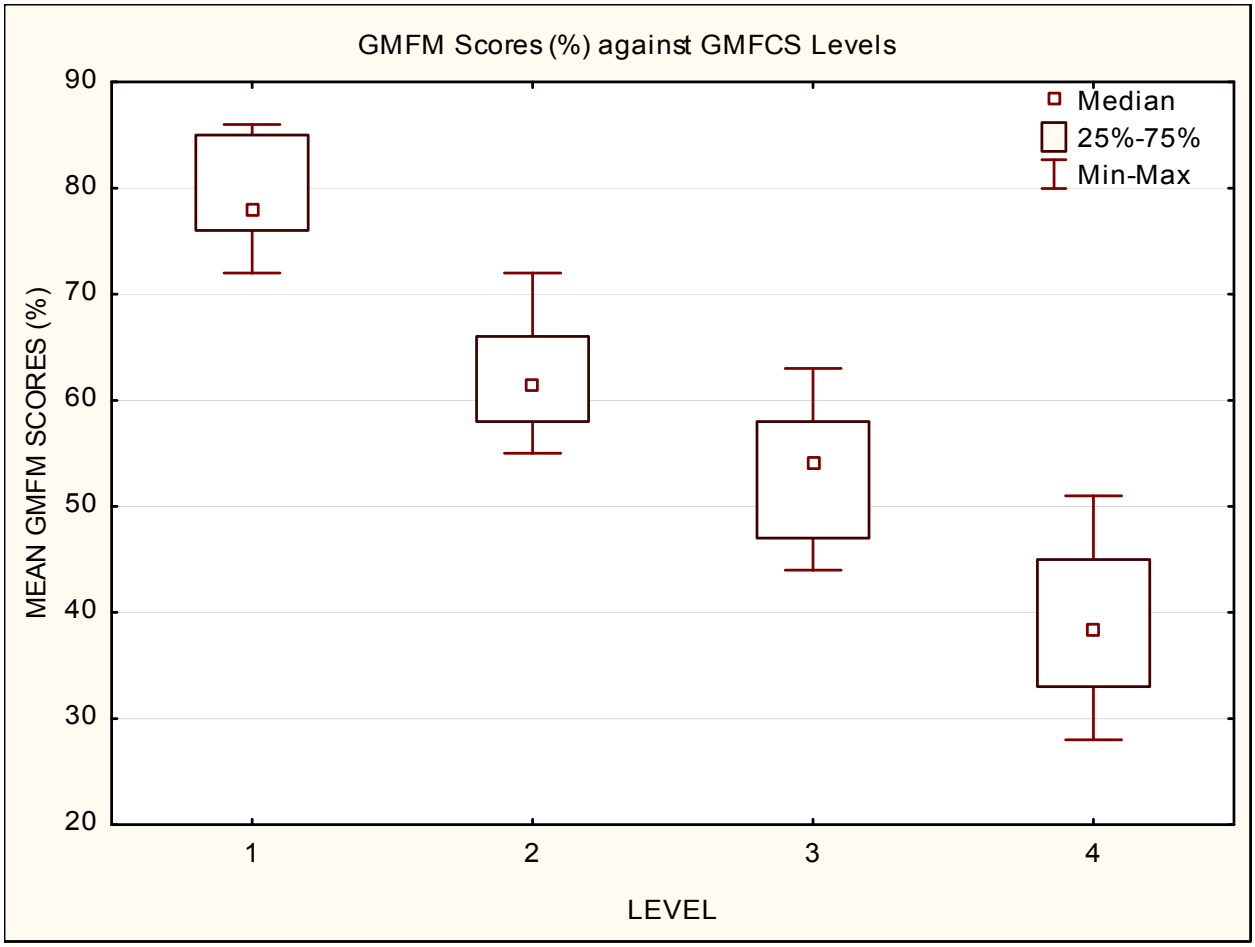


Figure 25: Box-Whiskers Plot of the GMFM scores against the various GMFCS levels (N = 42)

Note that level 1 of the GMFCS grading denotes mild form of the condition while level 4 in this study stands for the severe form of spasticity.

4.8.3 Relationship between GMFM and muscle parameters

Table 37 below shows the Spearman's correlation between the GMFM and changes in muscle thickness during active and resting states. The only significant correlation found between the GMFM and the different parameters was with the change in IO thickness significant which was a positive correlation *rho* = 0.342, (p = 0.026).

Table 37: Spearman's Rank Order Correlation between GMFM and the change in muscle thickness and EMG activity (STCP; N = 42)

	Spearman - R	t(N-2)	p-value
EO Th dif norm	0.084	0.534	0.596
IO Th dif norm	0.342	2.305	0.026
TrA Th dif norm	0.113	0.718	0.477
RA Th dif norm	-0.007	-0.045	0.965
EO EMG dif	0.34	2.3	0.026
IO EMG dif	0.34	2.3	0.028
RA EMG dif	0.43	3.0	0.004

4.9 Scores for the physiological cost index (PCI) test

As the data were continuous and normally distributed in each group (Figure 26), parametric statistics were used except when comparisons with non-normal variables were made.

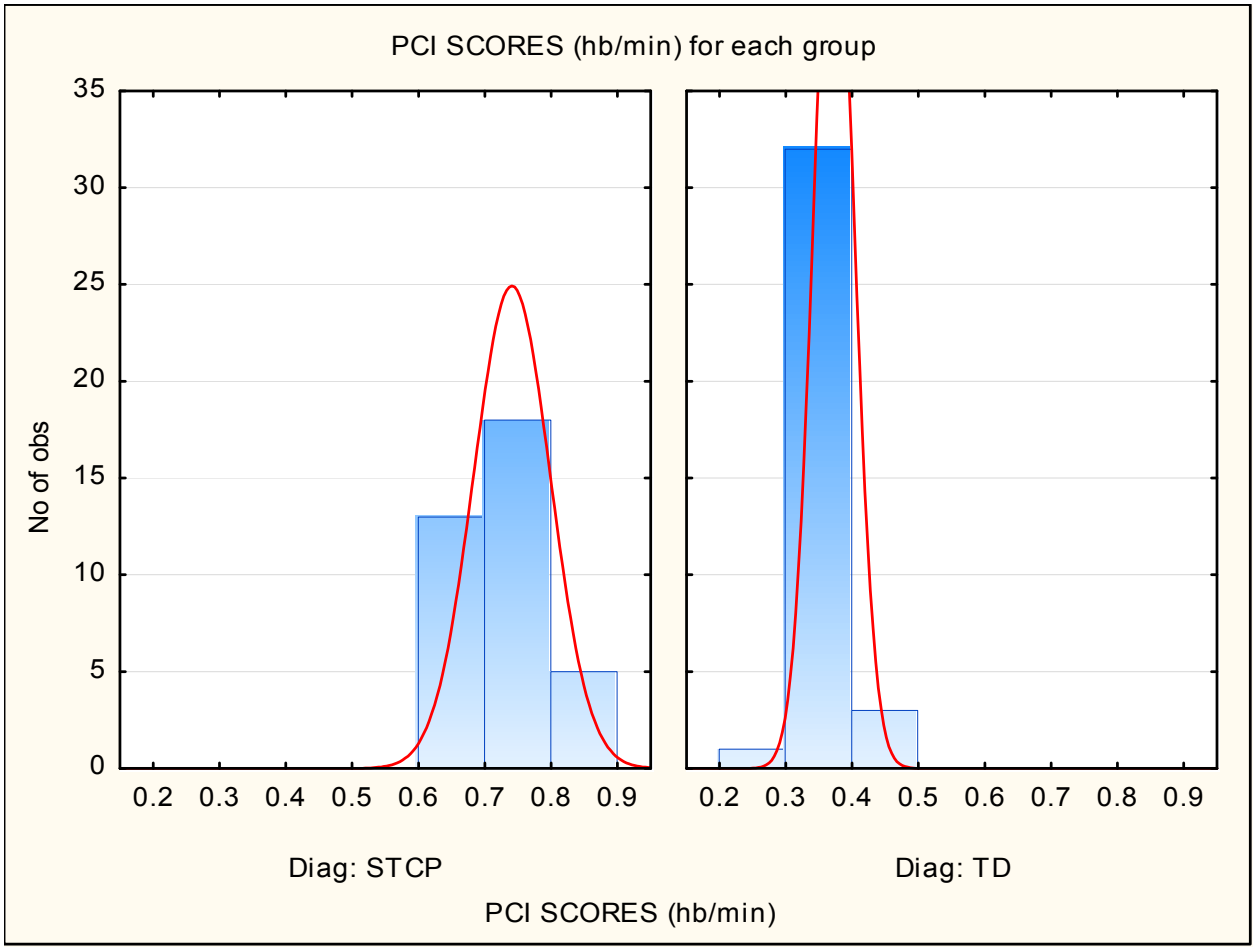


Figure 26: Histograms of the PCI scores (hb/m) for the two groups (N = 36 in each group). Shapiro Wilks = 0.958 (p = 0.190) in the STCP group and 0.953 (p = 0.134) in the TD group

4.9.1 Correlation between PCI and BMI and age

The correlation between BMI and PCI was negative in each group in other words as the age increased the PCI decreased as shown in Table 38 below. The correlation was very high in the STCP group, -0.961. There was no correlation between BMI and PCI.

Table 38: Spearman's rho between PCI and BMI and Age for the two groups (STCP: N = 36; TD: N = 36)

STCP	Valid - N	Spearman - R	p-value
PCI SCORES (hb/min) & Age/years	36	-0.961	$p < 0.001$
PCI SCORES (hb/min) & BMI	36	-0.084	0.625
TD			
PCI SCORES (hb/min) & Age/years	36	-0.72	$p < 0.001$
PCI SCORES (hb/min) & BMI	36	-0.21	0.211

The PCI was therefore normalised for age. However, when dependent statistics were calculated, such as correlations, the absolute values were used as the effect of division by the same age would result in a falsely inflated correlation co-efficient.

4.9.2 Correlation between PCI against GMFM

Analysis shows a significantly negative correlation exists between the GMFM scores and PCI, (*rho* = -0.53, p = 0.002). In other words, the lower the GMFM score, the greater the energy expenditure. A graphical representation of the relationship between PCI scores and disability levels is displayed in Figure 27 below.

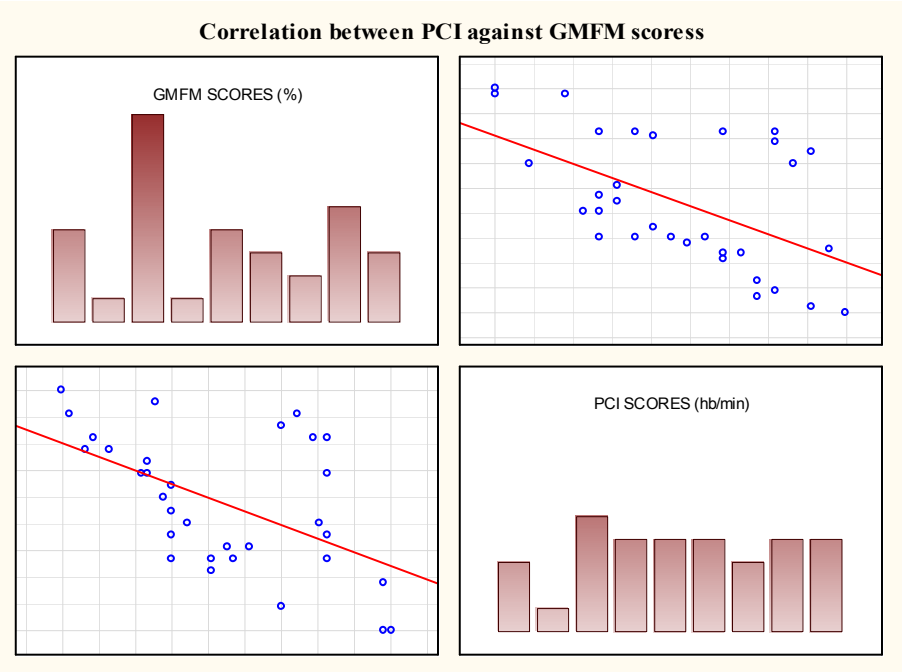


Figure 27: Energy expenditure measured by PCI against disability (GMFM) levels (N = 36)

4.9.3 PCI, muscle parameters and EMG

Table 39: Correlation between PCI scores and changes in muscle thickness and EMG activity

	Valid STCP	Spearman	p-value	Valid TD	Spearman	p-value
PCI SCORES (hb/min) & EO dif Th	36	0.27	0.11	36	0.199	0.245
PCI SCORES (hb/min) & IO dif Th	36	0.26	0.12	36	0.058	0.736
PCI SCORES (hb/min) & TrA dif Th	36	0.13	0.46	36	0.413	0.012
PCI SCORES (hb/min) & RA dif Th	36	-0.06	0.73	36	-0.297	0.088
PCI SCORES (hb/min) & EO EMG dif	36	-0.09	0.6	36	-0.277	0.102
PCI SCORES (hb/min) & IO EMG dif	36	-0.14	0.41	36	-0.291	0.086
PCI SCORES (hb/min) & RA EMG dif	36	-0.21	0.21	36	-0.423	0.01

As shown in Table 39 above, there was no clear pattern of correlation with PCI and muscle parameters or thickness in either group, although the PCI increased significantly in the TD group with an increase in change in TrA and decreased significantly with an increase in RA thickness and change in RA EMG. Visual inspection of the scatterplots identified two outliers in the RA dif plot and once these were excluded, the significant correlation between PCI and change in RA thickness disappeared.

Table 40: Spearman's Rank Order Correlation between PCI and the change in muscle thickness and EMG (STCP; N = 36, TD; N = 36)

	Valid STCP	Spearman	p-value	Valid TD	Spearman	p-value
PCI SCORES (hb/min) & EO dif Th	36	0.27	0.11	36	0.199	0.245
PCI SCORES (hb/min) & IO dif Th	36	0.26	0.12	36	0.058	0.736
PCI SCORES (hb/min) & TrA dif Th	36	0.13	0.46	36	0.413	0.012
PCI SCORES (hb/min) & RA dif Th	36	-0.06	0.73	36	-0.297	0.088
PCI SCORES (hb/min) & EO EMG dif	36	-0.09	0.60	36	-0.277	0.102
PCI SCORES (hb/min) & IO EMG dif	36	-0.14	0.41	36	-0.291	0.086
PCI SCORES (hb/min) & RA EMG dif	36	-0.21	0.21	36	-0.423	0.010

4.10 Comparison of muscle parameters across type of STCP and GMFCS levels

As can be seen in Table 41 below, the Kruskall Wallis ANOVA indicated that there was no difference in the mean ranking of any of the muscle parameters across any of the diagnoses. However, in most cases, (as shown in Table 41 below) the children with spastic quadriplegia had the greatest decrease in muscle thickness and the smallest increase in EMG change in score from rest to activity.

Table 41: Descriptive statistics for type STCP diagnosis and changes in muscle thickness from resting to active states (N = 63)

	Type of CP	Mean	SD	Mean ranks	H	P
		EO dif Th norm	EO dif Th norm			
EO dif Th norm	**Diplegia**	-0.022	0.005	33.4	0.963	0.618
	Quadriplegia	-0.036	0.008	24.4		
	Hemiplegia	-0.024	0.003	32.4		
IO dif Th norm	**Diplegia**	-0.033	0.006	25.7	2.595	0.273
	Quadriplegia	-0.033	0.011	28.6		
	Hemiplegia	-0.029	0.004	34.4		
TrA dif Th norm	**Diplegia**	-0.030	0.003	26.8	2.463	0.292
	Quadriplegia	-0.033	0.006	25.8		
	Hemiplegia	-0.024	0.002	34.4		
RA dif Th norm	**Diplegia**	0.034	0.004	35.46	1.168	0.558
	Quadriplegia	0.027	0.007	25.40		
	Hemiplegia	0.033	0.002	31.65		
EMG EO dif norm	**Diplegia**	2.517	0.310	31.3	0.324	0.852
	Quadriplegia	2.194	0.519	28.0		
	Hemiplegia	2.661	0.175	32.7		
EMG IO dif norm	**Diplegia**	2.321	0.302	28.3	1.775	0.412
	Quadriplegia	2.077	0.506	25.1		
	Hemiplegia	2.603	0.171	34.0		
EMG RA dif norm	**Diplegia**	7.407	0.553	30.0	0.225	0.893
	Quadriplegia	7.601	0.925	32.2		
	Hemiplegia	7.724	0.312	32.6		

Table 42: Descriptive statistics for changes in muscle thickness and EMG activity from resting to active states for affected and unaffected side of the hemiplegic group (N = 44)

	Mean	Std.Dv.
EO dif Th aff	-0.27	0.17
EO dif Th unaff	0.36	0.21
IO dif Th aff	-0.30	0.25
IO dif Th unaff	0.65	0.34
TrA dif Th aff	-0.28	0.14
TrA dif Th unaff	0.52	0.32
RA dif Th aff	0.37	0.18
RA dif Th unaff	0.45	0.22
EO EMG dif aff	37.98	2.24
EO EMG dif unaff	95.64	2.08
IO EMG dif aff	37.34	3.14
IO EMG dif unaff	98.89	1.88
RA EMG Dif aff	84.80	1.02
RA EMG Dif unaff	85.66	1.14

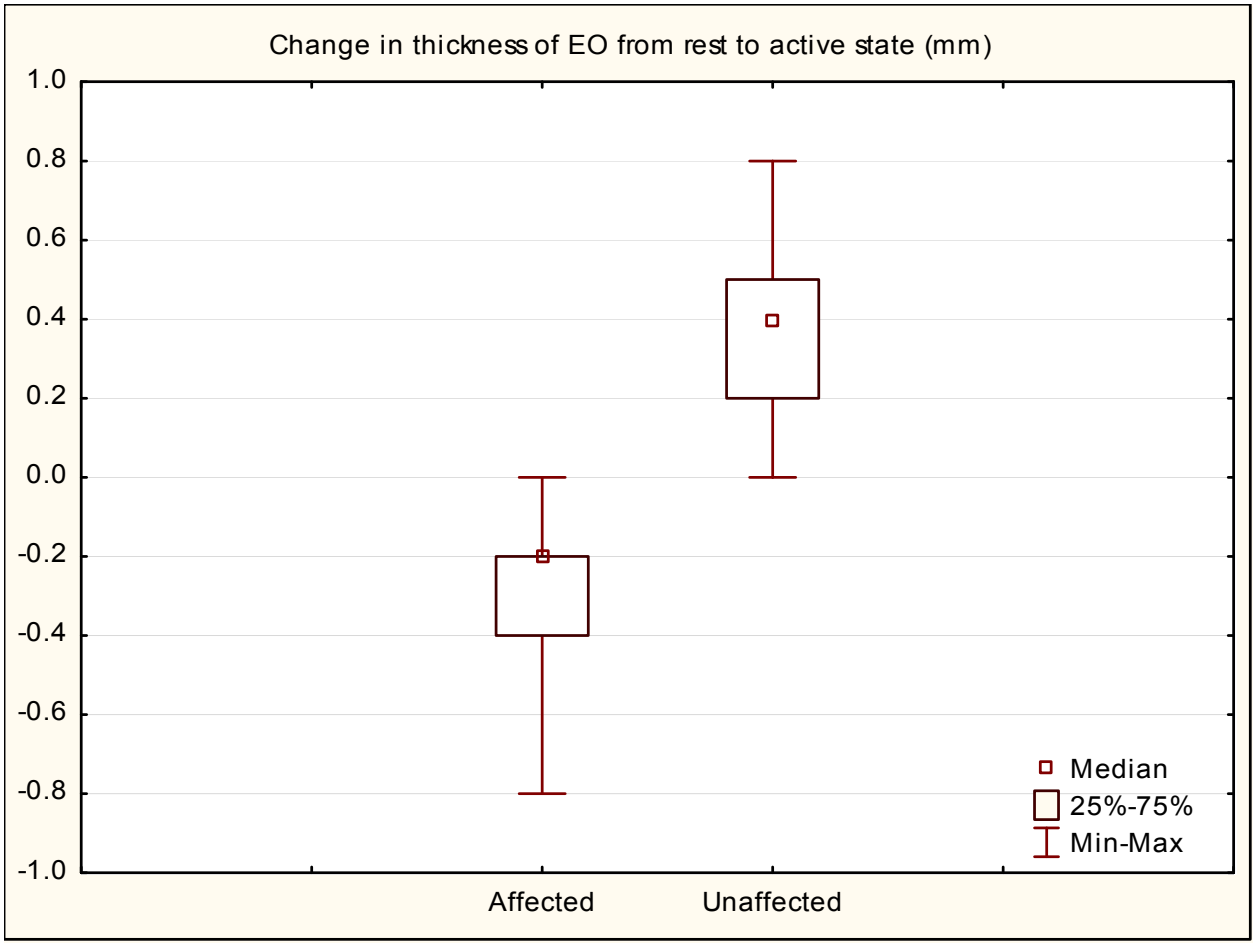


Figure 28: Box and whiskers plot of changes in EO thickness for resting to active states between the affected and unaffected side of the hemiplegic group

4.11 Comparison of abdominal muscle parameters between the affected and unaffected sides of children with spastic hemiplegia

For children with STCP who are hemiplegic, the changes in the parameters from the resting to the active states were analysed for the affected and unaffected side for each individuals, thus aligning with the pattern used for all parameters in the STCP and TD groups. Table 42 shows the results of the comparison of the changes in muscle thickness and EMG activity on contraction between the affected and unaffected muscles of hemiplegic individuals. There were no statistically significant differences in the changes in RA thickness as well as in the changes in the EMG activity of RA on either side. The box-and-whiskers plots for the changes in the thickness of the EO from resting to active states as shown in Figure 28, above, represent the general patterns of change for the other two anterolateral abdominal muscles

(IO & TrA). Note the similarity between the changes in thickness of the unaffected side of the EO and the changes observed for the TD muscles as already shown in Figure 18, above.

In twelve participants the changes in muscle thickness and EMG activity of the RA on the unaffected side were identical in value to changes on the affected side. An analysis of the remaining children (N = 32) revealed a statistically significant difference ($p < 0.001$) in the changes of thickness and EMG activity in RA between the affected and unaffected side using the Wilcoxon paired match test (Table 43).

Table 43: Wilcoxon's matched pairs test for dependent variables for changes in muscle thickness and EMG activity from resting to active states for affected and unaffected side of the hemiplegic group (N = 44)

	Valid	T	Z	p-value
EO dif Th aff & EO dif Th unaff	44	0.0	5.78	< 0.001
IO dif Th aff & IO dif Th unaff	44	1.0	5.77	< 0.001
TrA dif Th aff & TrA dif Th unaff	44	0.0	5.78	< 0.001
RA dif Th aff & RA dif Th unaff	37	218.5	2.01	0.045
RA dif Th aff & EO EMG dif aff	44	0.0	5.78	< 0.001
EO EMG dif aff & EO EMG dif unaff	44	0.0	5.78	< 0.001
IO EMG dif aff & IO EMG dif unaff	44	0.0	5.78	< 0.001
RA EMG dif aff & RA EMG dif unaff	32	86.0	3.33	0.001

4.12 Summary of the results

There were several interesting results that emerged and this section briefly summarises the most important findings;

- The RA was found to be thickest, followed by IO, EO and TrA in both groups. The pennation were small and there was no pennation angle for RA
- Most of the parameters were well correlated with age and to a lesser extent with BMI.

- The resting and active muscle thicknesses, PA and FL were all highly correlated within muscles and generally correlated to a weaker extent with the other muscle groups.

- At rest all of the muscles of the STCP group were significantly thicker, apart from IO. The IO muscle was the only one that was significantly different between the two groups in the contracted state and was thicker in the children with TD.

- On contraction, all of the muscles in the STCP *decreased* in thickness, with the exception of RA, whereas all the TD group muscles increased in thickness. Similarly the pennation angles of the muscles of the STCP group (which excluded RA) *decreased* whereas the angle *increased* in all the muscles of the TD group. Fibre length did not follow this pattern – all muscle fibres decreased in length in both groups.

- The muscle fibre length, decreased across all muscle groups except, surprisingly in TrA in the TD group in which the decrease was not significant.

- The EMG activity increased for both groups from the resting to the active state but far more so in the TD group.

- EMG activity was negatively correlated with age and, in TD children BMI was similarly found to be significantly negatively correlated, in other words the older and heavier the TD children were, the lower their resting and active EMG activity.

- EMG was not correlated within muscles from the resting to the active state in any muscle. However, there was a high correlation between all resting muscles and all active muscles. The lowest correlation with the other muscles was for RA.

- There was no correlation between EMG and the change in muscle thickness.

- The greatest difference between the two groups was seen in the change in muscle parameters from the resting to contracted states. The change in thickness, pennation angle, and EMG of all muscle groups was consistently significantly greater in the TD group.

- The GMFM scores significantly discriminated between the four GMFCS levels. However, there was no correlation between the amount of change in any parameter (thickness, pennation angle or EMG) and the GMFM score.

- The PCI was significantly greater for the STCP group than the for individuals with TD. There was no difference in PCI between GMFCS Level I and Level II, with the lowest level of PCI. The children at Level IV did have the highest PCI.

- Change in muscle thickness and EMG did not correlate with PCI.

- In every case, the responses of the RA in the STCP group most resembled that in the TD group.

- The unaffected side of children with the spastic hemiplegia showed similar changes from resting to active states as children with TD in all the muscle thickness whereas their affected side showed similar responses to the STCP group. EMG changes were significantly greater and positive on the unaffected side, compared to the decrease in thickness seen on the affected side.

- There was no evidence that the STCP group showed similar muscle architectural parameters (MAP) and EMG activity to a younger group of TD children. The parameters changed in parallel with different age groups.

There are noteworthy results for the muscle parameters, namely:

- The MAP's of RA in the STCP group showed different sets of characteristics compared with the three other abdominal muscles.

- The MAP's of RA in the STCP were similar to those from the TD group.

- The muscle thickness of the TD children and of the RA increased from rest to active state, as expected. In contrast the other three muscles decreased in thickness from the resting to the active state.

- Pennation angle for all muscles in both groups was so small (between 0° and 2.5°) that the abdominal muscles appear to represent a transition between pennate and non-pennate muscles.

Chapter 5 Discussion

5.1 Introduction

The aim of this chapter is to discuss the relevance of the results with regards to current anatomical knowledge and rehabilitation practices, thus exploring the relationship between theory and clinical practice from the structural and functional perspective of the abdominal muscles. The theme of this discussion is based on the role of the abdominal muscles in the maintenance of posture in individuals with spastic type cerebral palsy. The chapter also highlights the parallels between the results presented above and those from other studies on different parts of the body, especially the limbs. The internal validity of all the experimental procedures undertaken in this study will be discussed and critiqued. Finally, the statistical correlations of the MAP's and the findings of the other measures of outcome undertaken in this study and their implications on muscle impairment and interventions have also been discussed. First a short appraisal of the study sample is presented prior to the discussion on MAP.

5.2 Representativeness of the STCP sample

5.2.1 Sex

The sample was representative of the sex balance in children with STCP as is evidenced by the preponderance of males (55.6%) which was similarly reported in a study with a larger sample size of 586 children with cerebral palsy also reported a similar sex ratio of 56% males and 44% females (Palisano *et al.,* 2000). The sex balance in the current study compares with a similar study by Bartlett *et al*. (2010) with a sample size of 135 comprising 76 males and 59 females. Although the sex ratio in the current study was not statistically significant ($p = 0.423$) it is not clear how much of an influence this difference has on the final outcome as evaluated by the measurement of MAP's and EMG activity.

5.2.2 Distribution

There were more children with the spastic hemiplegia (69%) and fewer with the diplegic and quadriplegic subtypes (22% and 9%, respectively) than in other studies. A report by Palisano *et al*. (2000) indicated that individuals with spastic quadriplegia and diplegia constitute more than 70% of the sample in a cohort study (N =217), while the hemiplegic and triplegic subtypes of spasticity form only about 25%. Although the sample size for the STCP participants in the present study is bigger than many other similar studies (Crompton *et al*.,

2007; Ten-Berge *et al.,* 2007), there appear to be a disproportionate representation of the demography of the different subtypes. The epidemiology and reports of the incidence, prevalence and all the other indices that categorised any particular system of classification indicated that the demography of cerebral palsy varies from one population to another (Krageloh-Mann *et al.,* 1993; Blair & Stanley, 1997; Hagberg *et al.,* 2001; Gorter *et al*., 2004) and the discrepancy may be that the population in Cape Town is less affected. This is unlikely and a more reasonable explanation for the discrepancy could be the sampling from special schools in which only educable children are admitted. Spastic quadriplegia is associated with more severe mental involvement (Beckung & Hagberg, 2002; Kathuria *et al.,* 2012) and the sample is therefore only representative of those with less severe disability (Beckung & Hagberg, 2002).

5.2.3 GMFCS Levels

Based on the disability levels, 34 (54%) of the total STCP sample size (N = 63) in the current study were from GMFCS Level I, while 11 (17%) of them belong to GMFCS Level II, with 8 (13%) from the GMFCS Level III and 10 (16%) were from GMFCS Level IV. A similar level of disability representation was reported in the study by Gorter and colleagues (2004) in which more than one-third of their 500 sample size were from GMFCS Level I, with GMFCS Level II being least represented with 11% while the rest of participants were equally represented from the rest of the levels. Investigators in the Scandinavian populations with improved health care facilities for all categories of individuals with STCP also reported their study population of more than 600 to be skewed in favour of GMFCS Levels I and II. A study by Gangata (2008) in Cape Town also indicated that GMFCS Levels I and II form more than half of the study population, although the sample size was relatively small (N = 29).

However, the distribution of the GMFCS levels in the present study seems to differ from the demography of the participant in the study of Palisano and co-workers in which, apart from GMFCS Level I which is heavily represented (28%), the rest of the disability levels were fairly represented, including Level V which was excluded in the current study. The GMFCS (Level II is 13%, Level III is 19%, Level IV is 21% and Level V is 19%). The GMFCS Level V in the current study was part of the exclusion criteria in this study hence only four disability levels (GMFCS I – IV) were sampled. With a study population of 137 individuals with STCP, Hurvitz and co-workers (2007) documented over 60% of their sample was made up of participants diagnosed with GMFCS Levels III to V. As mentioned above, the

recruitment of children from schools that only admit educable children might have skewed the distribution.

5.2.4 Influence of age

The disparity between the distribution of the disability levels between the present study and other studies may be as a result of age differences in the various studies since age has been reported to influence the disability scaling (Wood and Rosebaum, 2000). Based on their study of more than 500 subjects with cerebral palsy, Gorter *et al*. (2004) reported that, when considering limb distribution, the quadriplegic and diplegic types are the predominant variety in younger age samples. While the present study recruited participants between seven and 16 years, Palisano and colleagues, worked with children of much younger age, from one to 12 years. It is worthy of note that in the current study, the experimenter, who is not a physiotherapist, could only extract the clinical diagnosis from the database of the participants in the schools and therefore had no direct assessment of these classifications. In a study such as this, which seeks among other things to correlate theoretical knowledge with clinical practice, an expert opinion would be necessary in such instances to validate existing data of the participants.

It can be concluded that this sample is representative of children with STCP who have a reasonably high level of cognitive function and the results presented may therefore not necessarily be generalised to all children with STCP. In addition, the limitation of depending on diagnostic categories recorded in the personal records of participants is acknowledged.

5.3 Muscle parameters

The three MAP's considered in the literature to be predictive of muscle strength (Abe *et al.,* 1999; Lieber & Friden, 2000; Ohata *et al.,* 2008; 2009) that were analysed in this study are muscle thickness (Th), pennation angle (PA) and muscle fibre / fascicle length (FL). In this section, the findings of each component of MAP's as measured and how this seeks to answer those specific objectives as outlined in chapter one have been discussed.

5.3.1 Muscle thickness

The measurements of the MAP's from this study were done through ultrasonography which provided only a two-dimensional view of skeletal muscles with a three-dimensional appearance *in vivo*, therefore it is also possible that not all of the architectural arrangement was captured. It is worth mentioning that to the best of the knowledge of this investigator no

such work has been conducted on the abdominal muscles in individuals with STCP and it is therefore challenging to relate the results of the abdominal parameters from the current study to any other available data. The ultrastructural studies on STCP available in the literature are skewed in favour of limb muscles, especially with the gastrocnemius and quadriceps femoris muscles. Similarly, the relatively few relevant studies on the abdominal muscles encountered in the literature are mainly on healthy adults, thereby rendering them incomparable since the current study focuses on children and adolescents with STCP.

Many studies of other parts of the body, especially the lower extremities in both healthy individuals and those with STCP, relate muscle thickness to muscle strength (Misuri *et al*., 1997, Binzoni *et al.,* 2001, Muramatsu *et al.,* 2002, Hodges *et al*., 2003). In the light of this approach, the current study will also follow the same argument by regarding muscle thickness as the prime muscle architecture predictive of muscle strength.

5.3.2 Relative muscle thickness

The observation that the thickness of RA in the STCP and TD groups was the greatest of all the abdominal muscles is important. Compared with the other three abdominal muscles, RA was consistently thickest both at rest and during active state in the STCP and TD groups, which concurs with other authors (Unger, 2011). Unger tested 34 children with a mean age of ten-years and four months-old years in the STCP group and nine-years and four-months-old in the TD group. The findings from the study of Unger (2011) as shown in Table 44 were very similar to the current study, in that the relative muscle thickness was almost the same in both groups, namely RA, IO, EO and TrA is the thinnest of all. The largest discrepancy between that study and the current one, was with regard to IO, which was reported as being somewhat thicker than in this study.

Table 44: Comparison of resting muscle thickness with the Unger (2012) study

Muscle	Thickness current study STCP/mm	Thickness Unger study STCP/mm	Thickness current study TD/mm	Thickness Unger study TD/mm
RA	6.3	7.6	5.4	5.2
IO	4.8	6.3	4.3	5.1
EO	3.6	3.7	3.1	3.2
TrA	2.9	2.6	2.1	2.6

No other comparable results for the abdominal muscles in STCP children were found in the literature, although other investigators such as Ohata *et al.* (2008); Legerlotz *et al.* (2010) and Moreau *et al*. (2010) did equate muscle thickness to muscle strength in subjects with cerebral palsy and reported greater values (> 12mm) in the lower limb muscles. The thickness of a muscle may contribute to muscle strength but how cerebral palsy impacts on the variations in thickness of the different abdominal muscles is still not fully understood.

An interesting finding was that, at rest, the STCP muscles were thicker than those of the TD children. The results of EMG test, also discussed below suggest that this relative thickness in muscle at rest may be related to increased tone. There was no evidence of muscle atrophy and also no available document relating muscle thickness to atrophy.

5.3.3 Change in thickness from resting to active state

At the macroscopic level, as muscle contracts concentrically, the attachments are brought closer together, whereas at the cellular level, there is an increasing overlap of the sarcomeres (Muramatsu *et al.,* 2002a). This overlap is reported to result in an increase in muscle thickness as reflected in the literature in lower limb muscles (Ohata *et al.,* 2008 and Legerlotz *et al.,* 2010). There are for example, reports of an increase in TrA thickness in healthy adults on contraction (Critchley, 2002; Critchley & Coutts, 2002). This was found to be the case in the TD children in the current study, in that all muscles became thicker. In contrast, with the exception of RA, the thickness of all muscle in the STCP group was less in the contracted than in the resting state and the oblique muscles of the STCP group appeared to be contracting less than the RA.

An actively contracting RA in the STCP group appeared to be necessary for the maintenance of posture and RA may have assumed a new role. In addition to the flexion of the trunk, the RA may be providing stability to the bony pelvis in order to maintain good posture during active contraction. This increased contraction of the RA may result in or be a consequence of the other abdominal muscles becoming inhibited and contracting less than when at the resting state. A similar decrease in abdominal muscle thickness from resting to active state was reported by Unger (2012) and also in rectus femoris and vastus lateralis in children and adolescents of children with STCP (Moreau *et al*., 2009, 2010).

However, many of the differences between the STCP and TD groups were not significant. The one measurement which did emerge as being significantly different was the change in

thickness of the RA, EO, IO and TrA between the resting and contracted states with the STCP group consistently showing a smaller change. The absolute figures in change in muscle thickness for the EO for instance, were approximately -0.02 (p = 0.48) for the STCP group and 0.02 (p = 1.32) in the TD group.

These subtle changes in muscle thickness as recorded for all the abdominal muscles in this study (refer to Table 14 and Figures 18 to 20), seem to cast doubt on the ability of these muscles in TD to generate sufficient force in order to stabilise the bony pelvis on contraction. However, when these changes in thickness are considered within the context that abdominal muscles are generally thin (between 3mm and 7mm – refer to Table 9), it can be argued that the observed changes in thickness are indeed large, especially when taking into account the fact that the majority of the participants were less than twelve-years-old (mainly pre-pubertal). Hodges *et al.* (2003) recorded no change in thickness for EO in healthy adults upon contraction, yet these investigators noted significant EMG activity between the resting and active states of EO. Therefore, this theory may apply to the present study / findings as well, in which small changes in thickness from resting to active state could account for muscle strength.

In the children with STCP the major problem does not seem to be to be the lack of muscle contractile material and therefore theoretically an inability to generate force. It rather appears that the children with STCP lack the ability to activate the muscle fibres and that this may be the major difference between the abdominal muscles of the two groups. This proposition is further discussed under the section on EMG.

5.3.4 RA muscle thickness and its role on pelvic stability

Many of the mechanisms by which these muscles change in thickness in the STCP and TD groups remain unclear but the data from the current study point to a dissimilarity in the contractile activities between the two obliques and TrA muscles on the sides of trunk and the rectus abdominis muscle located on the anterior abdominal wall. It appears as if RA is the only muscle in the STCP group that behaves in a similar manner to the abdominal muscles of the TD group. The different patterns of behaviour of the EO, IO and TrA muscles in the STCP group were more clearly evident for changes in thickness than in the other two architectural parameters investigated (PA and FL).

It is most likely that owing to the variations in the attachments of these muscles to the bony pelvis, differing changes to muscle thickness could be expected when contraction occurs in the RA on the one hand versus the oblique muscles. From the perspective of gross anatomy, it may be concluded that the variations in the change of thickness are partially as a result of differences in the morphology of these muscles. For instance, the EO and IO consist of a relatively modest proportion of fleshy belly (actual contractile portion) laterally on the trunk with a considerable amount of aponeurosis towards the sagittal plane (Moses *et al.,* 2005; Standring *et al*., 2005). This gross structural appearance is in sharp contrast to the midsagittally located RA which is mainly comprised of fleshy parts with relatively small bands of non-contractile tissue in the form of specialised tendons intersecting the longitudinally orientated bands of muscle at various points along its long axis (Moses *et al.,* 2005; Standring *et al*., 2005). For these abdominal muscles, the differences occurring in their gross morphology, attachments and specific effects on trunk stability, have been documented in other studies (Bergmark, (1989), Panjabi *et al. (*1992a) and Richardson *et al.* (2002) in which the RA was referred to as a "global muscle" playing a vital role in stabilising the bony pelvis on contraction, whereas the IO and TrA were regarded as "local muscles" which act as "moment producers" at the bony pelvis. The amount of connective tissue relative to the contractile component in these morphologically distinct muscles was not investigated in this study but the role of the connective tissue to muscle ratio, especially in the STCP group with respect to the differences in contraction should not be overlooked. What has not yet been documented is the extent to which this connective tissue may influence muscle activity (Fukunaga *et al.,* 2002; Maganaris & Paul, 2002; Davies *et al.,* 2007) and also the degree to which each of these two sets of muscles adapt to activity / contraction under pathological conditions. Hodges (2011) reported that the redistribution of muscle activity among muscle groups is a mechanical way of protecting other muscle tissues from further injury or pain. This is an area which requires further research as it may provide a clearer understanding of the overall functioning of abdominal muscles.

The contraction of muscles is known to be energy consuming and the overall energy demand of the body in individuals with STCP is already high (Raja *et. al.,* 2007). The results of muscle thickness from the present study lend support to the fact that a relatively thick RA adapts to become capable of inhibiting the contraction of a thin and poorly developed EO, IO and TrA. In individuals with STCP it is, therefore, suggested that this is a physiological means by which the body is able to conserve energy in these muscles while still attempting to

maintain a stable posture through the contraction of RA. Raja *et al.* (2007) noted that a stable posture is necessary for good cadence, and the realisation of an adequate cadence is an activity which demands energy in ambulatory children with STCP. From the results obtained on muscle thickness in this study, it could be deduced that any rehabilitation practice on the obliques and the transverse abdominal muscles, which is designed to conserve energy and at the same time enhance thickness, is likely to yield an optimum result with respect to the maintenance of posture.

5.3.5 Conclusion regarding muscle thickness

These results challenge the assumption that muscles thickness is the primary determinant of strength and functional ability, specifically as the resting thickness of the muscles of STCP was greater than observed in the TD group. This is speculated to be as a result of increased tone and a heightened state of contraction at rest. Although the muscles in the STCP group were thicken than in children with TD, they are unable to contract further and generate adequate force to stabilise the trunk (bony pelvis). Therefore, thickness as a parameter may not be related to muscle performance / strength. Rehabilitation intervention should therefore be aimed at decreasing tone, since increased tone appears to be related to thicker muscles and inability to generate optimal force for pelvic stability.

5.4 Pennation angle (PA)

Several studies on the limb muscles revealed that a large PA allows for a greater amount of material to be attached to a given area of the tendon (Wickiewicz *et al.,* 1983; Kawakami *et al.,* 2006; Iwanuma *et al*., 2011; Wakahara *et al*., 2012). The PA values that were recorded in this study were consistently small, (< 3°; SD = 0.23) across all muscles in both groups, which by inference means little contractile material could be packed into the muscle fibre in order to allow for the generation of that muscle force which could have any meaningful impact on the bony pelvis. It is mostly likely that the small PA of especially the TrA, the appearance and orientation of the muscle fibres contributed to this muscle being referred to as parallel muscle (McMeeken *et al.,* 2004). The pennation angles (PA's) of IO in both groups which were at their greatest during the active state were still consistently less than 3°. These small PA's recorded for all the abdominal muscles, including the IO may have been too small to be resolved prior to the advent of modern computing technology as well as current techniques involved in image analysis. Hitherto, the limitations in image resolution may have contributed to the erroneous categorisation of the abdominal muscles in older texts and the

literature as being pennate muscles (Wickiewicz *et al.,* 1983; Gans & Gaunt, 1991; Maganaris *et al.,* 1998).

The RA muscle from the STCP and TD groups showed a PA value of zero, implying that the fibres of this muscle are arranged parallel to the line of pull of the aponeurosis / tendon. This observation of RA showing PA of zero in the current study is made possible courtesy of the power of analysis of the modern software tool, IMAGE J (National Institute of Health, Bethesda, USA). It is through the realisation of a uniform PA of zero for the RA muscle from individuals in both groups that led to the exclusion of this muscle from the portion of the results in this study dealing with the pennation angle. These results of a PA of zero concur with the stripe-like morphology and longitudinally orientated nature of the fibres of the RA muscle, as can be observed on inspection of the gross morphology and the appearance of these fibres in dissected cadaveric materials (Tobias *et al.,* 1988; Moses *et al.,* 2005). The fact that the results of the PA of the RA muscle are the same in both groups from the resting to active states not only gave one the confidence that RA is a non-pennated muscle but also provides an indication that PA may not necessarily be a predictive parameter for muscle strength, or at least not for the RA muscle.

The PA for the obliques and transverse abdominal muscles in this study appear to have their fibres inserting close to the central axis of the aponeurosis, which represents the direction of the line of pull of these muscles. The PA results may, therefore, imply that these acute angulations, which range from as low as 0.5° to a maximum of 2.8°, could possibly impart a negligible force on the point of insertions of these muscles on the bony pelvis. This inference appears to be corroborated with reports from the literature which show that in classically pennated muscles, as found in the limbs, a large PA (18° – 45°) is the cosine component of the forces generated by the muscle fibres associated with the transmission of this force to the tendon (Brainerd & Azizi, 2005; Azizi & Brainerd, 2007; Iwanuma *et al*., 2011). The present results showed that even with TD individuals, in whom no malfunctioning of the abdominal muscles has been reported, small pennation angles were observed. It may suffice to describe the abdominal muscles as being atypical pennate muscles, representing a transition between between truly pennated muscles as found in the limbs and non-pennate / parallel muscles as found in the muscle of facial expression. This description is based on the observation that the RA which is situated in the median plane of the abdominal wall comprises non-pennated

fibres while the obliques as well as the transverse abdominal muscles located on the antero-lateral abdominal wall are poorly pennated (0.5° to 2.8°; SD = 0.2).

The functional implication of the heterogeneous nature in which the abdominal muscles are arranged with respect to pattern of pennation in relation to other muscles in the body, is beyond the scope of the current study but needs further investigation. It is most likely that the different patterns of pennation of the abdominal muscle fibres are designed to suit the various contraction modalities, (concentric, isometric or isotonic) which could help in conserving energy within the muscle fibre, while still being able to generate sufficient force.

5.4.1 Pennation angles and muscle thickness

In the light of some of these results, it could be inferred that PA may not be a significant indicator of muscle strength in these muscles. These small pennation angles coupled with the observation that the rectus abdominis (RA) muscle in both groups showed a pennation angle of zero makes it difficult to relate PA of the abdominal muscles to muscle strength. Results from the present study indicate that RA muscle is made up of parallel muscle fibres with no evidence of any angulated attachment of the fibres to the force of pull of the tendon / aponeurosis. This observation weakens any argument for the existence of a direct correlation between PA of the abdominal muscles and the production of muscle force, in contrast to that found in lower limb muscles (Kawakami *et al.*, 2006; Legerlotz *et al*., 2010).

In the limb muscles, where PA values were reported to range from a minimum of 18° in the triceps brachii, over 20° in the vasti muscles and between 20° and 40 ° in the gastrocnemius (Binzoni *et al*., 2001; Kawakami *et al.,* 2006; Iwanuma *et al*., 2011; Wakahara *et al.,* 2012), it is prudent to relate PA to muscle strength on account of these large pennation angles in these skeletal muscles. From the current study PA of zero was recorded for the RA muscles in both the STCP and TD groups while in the obliques and transverse abdominal muscles PA of less than 3° was observed. A hasty inference of the existence of an association between PA (0.5° to 2.8°; SD = 0.2) seen in the other three abdominal muscles (EO, IO and TrA) and muscle strength could imply that the RA muscle in both groups is a weak muscle or incapable of generating muscle force. The results of EMG activity (as discussed below) show that although no PA was recorded for the RA, this muscle appear to be the most physiologically active abdominal muscle. Therefore, PA essentially may not be associated with muscle activity and as such muscle strength.

A correlation among the various parameters showed a strong relationship between muscle thickness and pennation angle. This positive correlation is suggestive of the fact that PA could also be influencing muscle strength much the same way as muscle thickness. Furthermore, the similarities in the trends seen in the changes in muscle thickness and pennation angle, as shown in the tables and figures of the results chapter, is supportive of the fact that PA may predict muscle strength in much the same way as discussed for muscle thickness. This is the expectation should the correlation that exists between thickness and muscle strength as reported in the lower limb muscles (Kawakami *et al.*, 2006; Legerlotz *et al*., 2010) also be reflected in the abdominal muscles. In addition to muscle thickness, Kawakami *et al.* (2006) showed that there is a positive association between muscle thickness and pennation angle across individuals and thus concluded that PA follows muscle thickness in predicting the strength of a skeletal muscle. This positive correlation between muscle thickness and pennation angle needs to be established first in the abdominal muscles as suggested for the limb muscles. Lack of a documented evidence of this association between muscle thickness and PA for the abdominal muscles implies that the discussions on this parameter in this section is based on the assumptions that what pertains in the lower limb muscles could be the case in the abdominal muscles as well.

The results in Table 23 and Figure 22 showed a significant difference ($p < 0.001$) between the STCP and TD groups of the change in PA from the resting to active states. This change in PA indicates that a positive change was recorded in the TD group in which the strength of abdominal muscles was regarded as being intact in contrast to the STCP group in which negative or no changes in PA was recorded. It is thus tempting to presume on account of this significant difference between the two groups of the changes in PA from resting to active states, that PA is an active parameter in determining muscle activity.

The EO, IO and TrA that appear to be pennated could not be likened to the limb muscles with a large PA, therefore to imply that the PA in the abdominal muscles is significant in generating muscle force would be without adequate scientific and statistical supporting evidence. However, given that the PA of TrA was statistically greater ($p < 0.001$) at rest in the STCP group than the TD group and also considering the observation that PA in EO and IO of the TD individuals were significantly larger ($p < 0.001$) during the active state, this may point to the PA as a parameter that could also have some influence on the generation of muscle force. The role of PA in the activity of abdominal muscles may not be lucid, given the results discussed above for all the muscles in both groups during resting and active states,

but as has been documented, PA may be related to the transmission of efficiency of force to the tendon / aponeurosis with muscle thickness wholly related to muscle strength (Damiano *et al.,* 2000; Blazevich, 2006; Ema *et al*., 2013).

5.5 Muscle parameters – fibre length

Fibre length decreased from rest to active state in all muscles in both groups. This is in contrast to the trend shown by the other two architectural parameters in this study in that the muscles of the STCP group showed a different pattern to those of the TD group (with the exception of RA). In the literature, there are many schools of thought on the correlation between FL and the generation of muscle force with respect to lower limb muscles in children with STCP (Wickiewicz *et al.,* 1983; Kawakami *et al*., 1993; Binzoni *et al.,* 2001; Shortland *et al.,* 2002, 2004; Mohagheghi *et al.,* 2007, Legerlotz *et al.,* 2010, Moreau *et al.,* 2010 & 2013). The importance of FL in the generation of muscle force is linked to the behaviour of serial sarcomeres in a muscle fibre during contraction (Binzoni *et al.,* 2001; Mohagheghi *et al.,* 2007). However, as to whether there was a decrease in fibre / fascicle length from resting to active states in the present study as predicted by other authors in their studies (Binzoni *et al.,* 2001) could not be determined in the current study. Furthermore, discussions about the trends for FL with respect to reports from other studies may lack depth because different methodologies were used to arrive at the measurement of this parameter. For example, Moreau *et al*. (2013) used a virtual extrapolation method to extract the values of FL for the rectus femoris muscle using IMAGE J software from the sonogaphs. In the current study as well as in many other studies, (Binzoni *et al.,* 2001, Mohagheghi *et al*., 2007; Moreau *et al.,* 2009 & 2010), FL was measured as a derived parameter from both muscle thickness (Th) and pennation angle (PA), using the arithmetic formula: FL = Th / sinPA. The ICC scores for the calculations of FL in this study were fairly high ($r > 0.70$) (refer to Appendices C 1 and 2). The Spearman's *rho* for the FL between muscles during resting and active states was also high, 0.53 (EO) to 0.75 (IO). All these statistics on the derivation of the FL indicate reliability and thus could eliminate or reduce measurement errors to acceptable limits.

Another limitation regarding the non-invasive measurements of FL, such as obtained with the ultrasound imaging is the inability to quantify actual sarcomere length that would have been ideal in relating the changes in fascicle / fibre length to muscle strength. Therefore, an increase or decrease in FL still only leaves room for an inference that sarcomeres may have

either increased or decreased in series. Ultrasound measures a two dimensional view of the PA in the muscles rather than the three dimensional orientation in which they exist *in vivo* (Aggeloussis *et al.,* 2009) and it is from these pennation angle that FL is derived. Therefore this is a potential source of limitation for a parameter that may be regarded as having gone through serial derivations.

Muscle architecture is primarily described by FL and PA in healthy adults as being essential for muscle function and activity (Muramatsu *et al*., 2002; Aggeloussis *et al.,* 2009) but in this study in which PA was found to be very small (between 0° and 2.5°) and FL being a derived parameter, it is may be prudent to ignore the hypothesis that fibre length is a predictive parameter for muscle strength. It has been documented that mal-alignment of the probe to the plane of fascicles may affect fascicle length (Mohagheghi *et al*., 2007; Farris & Sawicki, 2012) and that an optimal FL is always difficult to assess (Farris and Sawicki, 2012), however, to the best of ability of this investigator, the probe was held perpendicularly to the orientation of the respective muscle fibres, which is the standard practice (Binzoni *et al.,* 2001, Ohata *et al.,* 2006, 2008, Mohagheghi *et al*., 2007, Legerlotz *et al.,* 2010, Moreau *et al.,* 2010).

Studies in healthy adults using a similar method found the fibre length of the medial gastrocnemius muscle to be shorter than the lateral fibres and ranged from 40 and 42 mm (Legerlotz *et al*., 2010, Smith *et al*., 2011). In the present study, FL ranged between 96.2 mm in TrA active for children in the STCP group to about 129.7mm in RA active in the STCP group. Because there is lack of data on FL of abdominal muscles in children with STCP in the literature, references have been made to FL in limb muscles of healthy adults. This again is another setback on the validity of FL in the present study as a major muscle parameter predictive of muscle function.

The confidence level of FL as being predictive of muscle strength is further decreased by the following observation:

- Failure to follow a reliable pattern as shown by the other two architectural parameters (Th and PA) measured in both groups in this study.
- That FL is a derived parameter, and
- That FL was unusually long to be considered as an ultrastructural measurement.

Due to the fact that FL in this study is a derived parameter, unlike Th and PA that were measured directly from sonographic images, it therefore, renders this particular muscle architectural parameter (MAP) less reliable as one of the primary predictors of muscle strength. In the light of the aforementioned shortfalls concerning FL, a consideration of this MAP as being predictive of muscle function in children with STCP, will not be discussed any further.

5.6 Muscle activity and sEMG

5.6.1 EMG at rest

The normed EMG activity was considerably higher at rest in the STCP children, apart from RA which was the same when compared to children that of children with TD. Similarly the muscles were also thicker at rest in the STCP group. As increased tone is a defining characteristic of STCP, both of these could be a reflection of increased tone due to increased and uninhibited recruitment of the motor neurones in these muscles. This increase in resting activity may be responsible for the decreased performance in that these muscles fibres have been in a prolong state of fatigue prior to the demand of work output (active state) negatively affecting their ability to optimally contract. Some investigators such as Suzuki *et al*. (2002) and Dario *et al*. (2004) have documented that an increase in EMG frequency (and *not* amplitude) is indicative of muscle fatigue. The current results indicated higher EMG frequency in the individuals with STCP during the resting and active states than for TD individuals and is indicative of an alteration in the electrical activity of these muscles at the ultrastructural level. That exact neuromuscular activity that dictates the mechanism by which EO and IO muscle fibres fire / recruit as many motor end plates in order to sustain an increase tone while at rest is still not clear. However, as seen from the results above, despite the higher EMG activity at rest for the oblique muscles in the STCP group, it is rather the muscles from the TD group and the RA of the STCP group that showed greater changes in EMG activity on contraction (refer to Table 32).

5.6.2 The changes in EMG activity from resting to active state between the STCP and TD groups

The dominance in muscle activity was made evident in the performance of functional tasks with a significant difference in the changes in EMG activity from resting to active states between the two groups ($p < 0.001$ for EO and IO and $p = 0.074$ for RA). Generally, the EMG activity increased for both groups from resting to the active state but far more so in the

TD group. During the active state, however, external and internal oblique muscle fibres in children with STCP showed an inability to synchronise the firing rate of all the already activated motor units. This therefore may account for the variance between the two groups in terms of changes in EMG activity from the resting to active states (refer to Table 29). It is likely that with the performance of a functional task (active state), muscle fatigue may have set in, thereby leading to the inability of these muscles to harmonise the electrical activity of all the motor units. It could therefore be inferred that, upon contraction, the overall implication of this muscle fatigue on the electrical activity of the EO and IO fibres is that fewer motor units are being recruited for the required action, accounting for the variance between the two groups ($p < 0.001$). In individuals with STCP the raw EMG activity for the obliques was significantly high ($p < 0.001$) which, seems to point to the fact that there may be increased tone in these muscles.

The pattern of change observed in the EMG recordings was surprising. There was an increasing EMG frequency with a decreasing muscle thickness in the children which STCP which might indicate that the muscles are being fired but that they are being prevented from contracting optimally. This type of static or even eccentric activity may be incapable of producing any force at the bony pelvis. This explanation, however, may represent an over-simplification of the complex relationship between EMG activity and muscle performance since several factors may result in an increased EMG frequency (muscle activity), including age.

Several authors have concluded that a high magnitude in Hertz units between the resting and active states (change in EMG frequency) signifies the strength of contraction (Suzuki *et al*., 2002; McMeeken *et al.,* 2004; Dario *et al*., 2004; Fosang & Baker, 2006; Chapman *et al.,* 2008). In the present study there were significant increases in EMG frequency from resting to active states in both groups but with the STCP group showing slightly lower scores (refer to Table 29). With regards to the changes in EMG activity from resting to contracted states, the STCP group showed significantly lower scores (refer to Table 29 than that in the TD group, however, the active state scores are somewhat comparable between the two groups. This variance in change in EMG activity might explain the difference in performance of the abdominal muscles between the two groups in terms of stabilising the bony pelvis. The change for the STCP group may be regarded as weak and probably could be summed up as a lack of synchronisation between the depolarisation and repolarisation phases of the motor

end-plate activities during the resting and active states. The occurrence or the absence of these physiological events might represent the concept of "fatigue" in muscle groups with increased tone (Prosser *et al*., 2010). In the case of the EO and IO in the STCP group, several motor units may be activated / fired during the contracted phase but given the significantly higher EMG scores at rest it is difficult to equate this active state result to optimal performance in these muscles. It is not clear whether new motor units were recruited in addition to the already activated / fired ones (to maintain tone) or only new motor end plates have been recruited exclusively during the act of performing a task, in contributing towards the final active state scores. However, there are reports of the recruitment of new motor units with a reduced EMG activity in the abdominal muscles of adults with low back pain (Chapman *et al*., 2008; Tucker & Hodges, 2010).

However, available evidence showed that, on contraction, the EMG activity increases marginally in the STCP group affirming decreased ability to generate a force but not the lack of recruitment of fibres. The EMG frequency is reported to correspond to recruitment patterns but not necessarily referring to performance levels (Nicholson *et al.,* 2001; Prosser *et al*., 2010). Should the active state EMG frequency scores in the STCP group have decreased below the resting state scores, it could have been interpreted as inability to recruit additional (new) motor end-plates for the specific tasks. From the present observation in which the contracted state EMG scores were consistently higher than recorded during the resting state (Table 40 above) it may lead to speculations that there is lack of harmony in the electrical activities between the muscle fibres that were activated for the maintenance of tone and those recruited for the performance of a specific task in the STCP group. A possible explanation for this could be that for the EO and IO in the STCP group, little or no force is generated towards moving or stabilising the trunk / bony pelvis. This is likely to be the case since the state of the electrical activities in the oblique abdominal muscles for the children with STCP is characterised by an initial (resting state) high EMG frequency scores which renders the active state score ineffective in the relation to performance or force generation. A similar observation was made by McMeeken *et al*. (2004) on the TrA in adults while using fine needle technique to probe deeper abdominal muscle activity during hollowing exercise. In comparison to children with TD, there is a disproportionate change in EMG frequency in the EO and IO between the contracted and relaxed states in response to any increased work output.

5.6.3 Comparison of the changes in EMG activity from resting to active states among the different abdominal muscles

In contrast to the other two abdominal muscles (EO and IO), the RA muscle in the STCP group showed electrical activity typical of TD individuals. It is clear that if high EMG scores at rest signify spasticity / increased tone and or muscle weakness, then neither of these characterised the RA muscle in the children with STCP. What may be inferred from this muscle in the STCP group and also for the rest of the muscles in the TD group is that significantly lower EMG scores ($p < 0.001$) were recorded during the resting (refer to Tables 29 and 30). The RA in the STCP group as well as all the muscles in the TD group appears to be relaxed with optimal tone and therefore able to activate sufficient motor units during activity. Low muscle tone during resting stage indicates healthy muscle activity (Bakke *et al.,* 1992) since any healthy muscle at rest exhibits a low EMG frequency but never a score of zero. The RA with such low EMG scores at rest may imply that during contraction all the depolarisation of the motor units become effective in reflecting the true state of the electrical activity of this muscle. This is in contrast to the obliques where it is most probable that some of the depolarised waves may be engaged in the re-activation of the already polarised motor end-plates (the lack of synchronisation concept discussed earlier on). Therefore, it suffices to infer considering abdominal muscles in children with STCP that the RA is least or not affected and hence this muscle could be targeted during rehabilitation procedures in order to provide the necessary contraction required to stabilise the bony pelvis / trunk.

This inference may be plausible theoretically, however no association existed between EMG activity in the resting and active state for the abdominal muscles (refer to Table 33) in the STCP group. Electrical activity of one muscle relative to the other(s) resulted in mixed outcome. When comparing RA activity to EO and RA with the IO at rest and during activity in the STCP results suggest that there is no overflow between the other muscles and the RA. This observation seems plausible given the location of these anterolateral muscles with respect to the RA. From the gross perspective, the fleshy and contractile portions in which electrical signals are generated from the anterolaterally placed EO and IO are further away from the sagittally located RA. The EO and IO approximate the RA in the median plane by means of non-contractile aponeurotic fibres. This could mean that the possibility of "cross-talk" between the RA and the other muscles on contraction is anatomically incapable of occurring. It may be argued that the electrical activity generated within the muscle fibres would not be able to polarise the intervening, non-contractile tissue such as the aponeurosis

found between the RA and these other abdominal muscles. It is therefore possible, to infer from these observations that a contracted RA may not necessarily assume a conjugate function of any of the neighbouring (spastic) muscles. Based on this evidence it appears that strengthening of the RA is unlikely to improve the function of the other muscles.

The Spearman's correlation results of the EMG activity between muscles at the resting and active states also revealed that RA in the STCP group is acting as an outlier by showing a positive figure. This is another indication that the observations made on the RA all this far may be reliable (refer to Tables 33 and 35).

This statistical analysis on the EMG activity amongst the three abdominal muscles at rest seems suggestive that there is an overflow of electrical activity among the various muscles during the resting phase. This is often referred to as "cross-talks" in the literature (Hodges and Richardson, 1998). Such an overflow of electrical activity is practically possible, given the fact that these muscles are thin in nature with thin fascial sheaths separating the various muscle groups. The use of surface electromyography (sEMG) technique may also have accentuated this "cross-talk" among the individual muscles (Tucker & Hodges, 2010). It is upon the basis of the avoidance of an overlapping electrical activity between IO and the TrA muscles that the deeper lying TrA was excluded from this EMG analysis since the placement of the electrodes for both muscles is usually at the same anatomical landmark (Bergmark, 1989; Hodges and Richardson, 1996; Cholewicki *et al.,* 1997; Wakeling *et al*., 2007). Any attempt to extract electrical activity from the TrA using sEMG would have meant that the final scores recorded could contain contributing signals from the overlying IO as well, which may then have implied a false inference. The possibility of false inferences should the TrA part of the test would have been practically difficult to adjudicate which score belongs to either the IO or TrA. An ideal method of monitoring the EMG activity for the TrA would have been by the use of the deeply placed fine wire technique, which due to its invasive nature could not be applicable to the children in this study. Therefore, with these high Spearman's r*ho* scores (0.73 - 0.93) in EMG activity among the various muscles at rest, it seems as justified to exclude the TrA from the EMG analysis.

5.6.4 Patterns of change in EMG activity and muscle thickness between the resting and active states

It appears the ultrasonographic measurements of these muscles seem to align with the electrical activity in the motor units as previously discussed. This pattern of abdominal

muscle thickness was also observed by Unger (2011), who suggested that thicker muscles at rest in individuals with STCP may be associated with increased tone. Hodges *et al.* (2003) reported no change in thickness of the abdominal muscles between resting and contracted states in individuals with STCP. Critchley & Coutts (2002) documented an increase in thickness of lower limb muscles in healthy adults. Other studies from the lower limb muscles of children and adolescents with STCP reported a decrease in thickness during contraction (Moreau *et al.,* 2009 & 2013). The change therefore in muscle thickness from rest to an active state in the STCP group as seen in the present study, could imply a relaxation of the muscle fibres and therefore, that the muscle in general is unable to generate sufficient force on contraction. In comparison to the muscles in the TD group and the RA of the STCP group, an increase in thickness from resting to active states may represent muscle activity and, then, directly or indirectly an indication of muscle strength. Muscle strength, however, was not measured in this study, but, arguably, the strength of the individual muscle was inferred from the electrical activity in the muscle fibres as evaluated by the EMG scores. It is not clear whether RA in the STCP group could take over the stabilising function of the other abdominal muscles with the change in thickness, which is indicative of muscle strength. However, there is supportive evidence from this study that EO, IO and TrA get thinner on contraction. Some investigators such as Moseley & Hodges (2005) and Vasseljen *et al*. (2006) reported on the lack of a consistent relationship between the changes in muscle and EMG activity in the IO and TrA muscles.

A selective pattern of muscle activation in the thigh muscles in response to voluntary movements has been reported by Zwaan *et al.* (2012); however, it is not clear if this is the case for the RA with regards to EMG activity in this study. The EMG results of the RA and the MAP's results of this muscle so far, appear to be conferring some kind of mosaic on the abdominal muscles as a group with the onset of STCP. This is because the RA typically showed electrical action much like the abdominal muscle of children with TD. How STCP could confer mosaic characteristics to a particular muscle within a muscle group has not yet been documented. In subsequent sections of this discussion, the relationship between electrical activity in the abdominal muscle and the gross motor function of individuals with STCP may help to explain this trend further. The implication of this result at this point is probably the need for further research into the utrastructural aspect of individual muscles within other muscle groups (for example, triceps brachii, quadriceps femoris, hamstrings, triceps surae and intrinsic back, hand / foot muscles) in individuals with STCP. This could

deepen the understanding of the behaviour of skeletal muscles in individuals with cerebral palsy and therefore sharpen the management skills of physical therapists.

5.6.5 Variations in the EMG activity of various muscles between the STCP and TD groups

Another significant difference between the STCP and TD group is the change in EMG activity from rest to active state. This change in EMG frequency in hertz units which has been inferred as equivalent to the overall active motor units in a muscle and thus muscle activity was significantly higher in the TD group than the STCP group ($p < 0.001$). Some studies have also reported a strong positive correlation between the changes in EMG activity and muscle strength (Hodges & Richardson, 1996 & 1998; Critchley, 2002; Critchley & Coutts, 2002; McMeeken *et al.,* 2004). This linear association between muscle strength and changes in EMG activity has also been reported to strongly correlate positively with muscle thickness in the masseter muscle of healthy adults (Bakke *et al.,* 1992). The quantum of change from resting to active state of the EMG activity is less in the STCP group than the TD group (refer to Table 29). As has been the case in MAP's and EMG for the RA, the change in EMG activity for the RA showed no significant difference between the two groups (RA_{STCP} = 85.1Hz, RA_{TD} = 85.6Hz). This may imply that a linear relationship exists between change in EMG frequency and the strength of RA in both groups. Muscle strength was not evaluated in this study, but this implication is based on reports from other studies which equated changes in EMG activity to muscle strength (Hodges & Richardson, 1996 & 1998; Critchley, 2002; Critchley & Coutts, 2002; McMeeken *et al.,* 2004). The possible explanation to the difference in the changes in the EMG activity between the two groups had already been explored – probably an increase in tone in the STCP group during rest with a consequential recruitment of more motor units during this stage. Similar patterns of changes in EMG frequency between the STCP and TD groups were also reported in the quadriceps femoris and hamstring muscles (Fosang & Baker, 2006; Moreau *et al.*, 2009; Merletti *et al.,* 2010; van Gestel *et al.,* 2012).

The variance in the changes in muscle thickness and EMG activity between the oblique abdominal muscles and RA in the STCP group with regards to the provision of trunk stability may possibly be explained using the concept of agonistic and antagonistic behaviour of skeletal muscles. It is likely that with the alteration of the neuromuscular system as associated with STCP, co-contraction takes place between the RA and the other abdominal muscles, similar to muscles acting as agonists and antagonists (Fellows *et al.,* 1994; Ikeda *et al*., 1998;

Damiano *et al*., 2000). Co-contraction for any reason in agonistic / antagonistic muscles has been shown to increase joint stiffness, which makes movement laborious (Fellows *et al.,* 1994; Ikeda *et al*., 1998; Damiano *et al*., 2000; Moseley & Hodges, 2005; Moreau *et al.,* 2011) and the rationale is that is what is observed with anterior pelvic tilt. If indeed co-contraction occurs between the RA and the other abdominal muscles in individuals with STCP (assuming these muscles are behaving as agonists and antagonists) then force production levels could only be maintained if the force of the agonist increased concurrently with an antagonist restraint. The result of this type of action between two physiologically different muscles is that the joint could become incrementally stiffer, a feature that is commonly evident at the bony pelvis and often associated with individuals with STCP and aptly referred to as pelvic tilt. These differences in the changes to muscle thickness and EMG activity between the EO and IO on the one hand and the RA on the other, in individuals with STCP mean that the possibility of co-contraction amongst abdominal muscles must not be overlooked during rehabilitation and management of these individuals.

5.6.6 Limitations to the use of EMG in this study

There should be careful interpretation of EMG scores such as those shown in the results chapter above in order not to draw inappropriate conclusions. Due to the complexity in the interpretation of EMG results, some investigators have advocated the use of motion mode ultrasonography to track muscle activity as an alternative to the use of EMG (Ohata *et al*., 2008; Vasseljen *et al*., 2009). The observations in this study were recorded in EMG frequency units (Hz) and not amplitudes, similar method has been used with validity and reliability documented (Lauer *et al.,* 2007a; Prosser *et al.,* 2010; van Gestel *et al.,* 2012). For EMG frequency as an evaluation tool, a decrease in muscle activity records an increase in EMG scores (Frigo & Crenna, 2009; van Gestel *et al.,* 2012). Therefore, the observation of no statistically significant difference of the EMG for RA between the two groups appears to concur with the MAP's results in which RA in the STCP group characteristically showed features similar to those of TD individuals.

5.6.7 Influence of age on MAP's and EMG activity

A positive association between age of the individual and muscle thickness was recorded: the older the child, the thicker the four muscles were in both groups. The onset of biomechanical and or hormonal mechanisms in these abdominal muscles predisposing them to alterations in

thickness in individuals with STCP may not be ruled out, but this is outside the scope of the current study.

This correlation between age and muscle thickness has also been reported in limb muscles (Binzoni *et al.,* 2001; Shortland *et al.,* 2002). Since muscle strength is reported to be closely related to muscle thickness in individuals with STCP (Ohata *et al.,* 2008; Legerlotz *et al.,* 2010), and as the muscles were noted to be thinner in younger children compared with older ones, this may imply that attempts at rehabilitation of the abdominal muscles for the maintenance of posture stand a better chance of yielding promising results in children with STCP when administered early in life. Analysis of the results obtained from pennation angle (PA) and age in this study indicates that the age of individuals correlated positively with PA in all groups with Spearman's *rho* ranging from 0.46 for EO active to 0.77 for TrA active ($p < 0.005$). However, a study on the medial gastrocnemius of healthy adults, showed a lack of correlation between PA and age *rho* = 0.26 to 0.32 (Legerlotz *et al*., 2010). In the present study, a weak association was found between PA and BMI with Spearman's correlation values ranging from 0.06 for IO active to 0.41 for TrA active ($p < 0.005$). This trend was also similar to that which was recorded for muscle thickness in both groups therefore there appears to be a high degree of certainty that excluding age, no other anthropometric data of the participants influenced PA of the abdominal muscles.

The strong correlation between young age and higher EMG frequency scores seems suggestive that, as the individual muscles become more refined in performing tasks with advancing age, then follows the recruitment of fewer motor units. In other words, generally there may be an increase in the recruitment of motor unit or firing in children of a younger age across both groups resulting in high EMG frequency scores. Similar observations were made in a study of muscle activity in the lower limb of children with STCP and TD (Lauer *et al*., 2010). This apparent similarity in the relationship between muscle activity and age in the two groups during the resting state seems to be an indication that muscle activity, rather than spasticity, may account for the variance observed in the gross motor functioning in individuals with STCP.

5.6.8 Correlation between changes in MAP's and the changes in EMG activity

There was no direct correlation observed between the changes in MAP's (as exemplified by the change in muscle thickness) and EMG frequency for individuals in the STCP group, whereas a weak association existed between these parameters for TD children (Table 35). In

this section only the change in the most reliable MAP, muscle thickness is considered. The lack of any association between the changes in muscle thickness and EMG activity could probably mean that prediction of muscle strength from muscle thickness may be inadequate, especially through the use of sEMG to record the underlying motor units, a position held by many other investigators (Damiano *et al.,* 2000; Suzuki *et al*., 2002; Goh *et al.,* 2006; Crompton *et al*., 2007; Vasseljen *et al*., 2009; van Gestel *et al.,* 2012). The lack of a correlation between the changes in muscle thickness and EMG activity may be as a result of other body structures which have been reported to contribute to muscle thickness but which differ from the active motor units of a muscle fibre and thus unable to influence EMG activity and its interpretation (Dario *et al.,* 2004; Wakeling *et al.,* 2007; van Gestel *et al*., 2012).

Although there was no direct correlation between changes in EMG activity and muscle thickness, the Spearman's *rho* scores in the present study agrees with the differences in trends observed between the EO and IO versus the RA in the STCP group. The changes in Th and the changes in EMG frequency showed a negative association for the EO and IO in the STCP group *(rho* = -0.386, p = 0.002; *rho* = -0.199, p = 0.117 respectively). On the other hand, a positive trend existed between these changes in the Th and EMG activity of the RA in the STCP group (*rho* = 0.329, p = 0.008). These correlations, though weak, nevertheless could further explain the difference in the trends seen between these muscles as has been discussed above.

With the STCP group, there was an increase in the change in muscle thickness with a corresponding decrease in a change in the EMG activity. This has been implied to mean muscle weakness or lack of synchronisation amongst the activated motor units. A moderately positive association with the TD group for these changes *(rho* = 0.5, p < 0.001) with a similar positive correlation recorded for the RA in the STCP group (*rho* = 0.329, p = 0.008). These trends in the Spearman's correlation test are another probability that changes in thickness in the TD group as well as RA of the STCP group could correspond to an increase in changes in EMG activity as evaluated in hertz units. In the TD group this may translate as the recruitment of more motor end-plates and therefore the production of greater force.

Therefore the Spearman's correlation between changes in Th and EMG activity also highlights the differences in behaviour between the EO and IO on one hand and the RA on the other hand, in the STCP group. The Spearman's correlation test showing a lack of association between the changes in muscle thickness and EMG activity in the STCP group is

still worthy of note. However, the discussions above are only possible explanations to the contrasting trends in the EO and IO muscles in the STCP group versus the muscles in the TD group as well as RA in the STCP. The ultimate difference between the individuals with STCP and TD children by way of the correlations with the changes in MAP's and EMG activity is probably as a result of poor recruitment of motor units at rest in the STCP group. The poor recruitment may have arisen from the increased tone in the spastic muscles, EO and IO which were thicker at rest in the STCP group than in the TD group.

5.7 Physiological cost index (PCI) and muscle activity

The children with STCP appear to expend higher levels of energy in walking (mean = 0.74 hb/min) than do their TD counterparts (mean = 0.34 hb/min) who used significantly less energy ($p < 0.001$). It could therefore be summarised that, an increased consumption of oxygen during walking seems to be associated with individuals with STCP. Whereas a negative correlation existed between PCI scores and age in both groups, the possible interpretation of this observation in individuals with STCP may have confirmed some of the earlier discussions made between MAP's and age. That is to say with increasing age, the individuals appear to have perfected skills needed for daily activity to the extent that there is less demand for the consumption of oxygen in the performance of these routine tasks. Alternatively, the present results most probably indicate that these older participant have adapted adequately to the condition of STCP that less energy is needed for the performance of daily task such as walking. This observation may imply that the burden of STCP lies heavily on younger individuals and therefore the impact of rehabilitation and intervention programmes may be greater in children of a younger age than in older ones.

However, the consumption of oxygen by way of PCI measurements showed no correlation with BMI (STCP: *rho* = -0.084, p = 0.625 and TD: *rho* = -0.21, p = 0.211). This could mean that the anthropometric characteristics of the participants may not have any direct relationship with the levels of oxygen consumption in the performance of daily activities such as walking. There was no correlation between either PCI and the changes in MAP (muscle thickness) or PCI and the changes in EMG activity of the two groups. When the PCI scores were correlated against the changes in muscle thickness, although there was a significant difference between the two groups in term of oxygen consumption during walking (Figure 12), no direct association was observed. It may therefore follow that, while individuals with STCP showed high PCI scores (mean 0.74 hb/min), the net oxygen consumption does not necessarily

translate specifically to the cellular level of the various abdominal muscles. It is likely that the high PCI scores could be as a result of the demands of other metabolic activities by these children. An example may be the physiological needs of the body of these individuals with STCP to keep taut ligament and sensory organs (eyes and ears) in an active state in order to provide a steady gait may involve the consumption of high oxygen that is likely to increase the PCI scores on assessment.

Similarly, the results from this study generally showed a lack of correlation between PCI and EMG activity in both groups (*rho* = -0.09 to -0.21; $p < 0.21$for STCP group while *rho* = -0.28 to -0.42, $p < 0.01$ for TD group). This result coupled with the observation that no clear association was observed between the PCI scores and the changes in muscle thickness as discussed above, seems suggestive that the recruitment of abdominal muscles in both groups may not be dependent on energy consumption levels of these muscles. However, further investigation is required to determine the composition of fibre-type present in these abdominal muscles since this is likely to influence the susceptibility of the muscles to impairment levels. Additionally, since some authors (Ijzerman *et al.,* 1999; Ijzerman & Nene, 2002) argue in favour of the use the direct oxygen uptake test in the correlation of MAP's and energy consumption, it may also be appropriate to have results from such a test before conclusions are drawn. The ability of these thin abdominal muscles to contract in order to provide stability to the strong and rigid bony pelvis may imply that cellular energy must be available but as to whether these muscles are made up of fast-twitch, low oxygen-demanding or slow-twitch, high oxygen-demanding fibres has not been documented. Rehabilitation in the form of muscle training is reported to have no alteration on the composition of fibre types (Stephenson, 2001; Forkey *et al.,* 2003; Neunhauserer *et al.,* 2011) and therefore PCI may not be linked to MAP's and the recruitment of motor units of a muscle. The responsiveness of PCI test as an outcome measure of MAP's and EMG activity of the abdominal muscles could only become relevant when these PCI scores are analysed alongside the fibre composition.

5.8 Descriptive characteristics of unusual results

5.8.1 Rectus abdominis (RA) muscle

Rectus abdominis (RA) was the only muscle in the STCP group that increased in thickness from the resting to active states. Unger (2011) also obtained similar results. The RA muscles in children with STCP increased in thickness upon contraction much the same as TD individuals. The change in thickness from resting to active at 95% confidence interval was

0.3 to 0.42 for the STCP group in comparison to the EO, IO and TrA which range from -0.39 to -0.23. This change in thickness between the two groups is significant ($p < 0.01$). Some studies have reported that a positive change in muscle thickness from the resting to active represents muscle strength (Stackhouse *et al.,* 2005; Urquhart *et al*., 2005). However, since abdominal muscles are reported to work independently with a collective effort in trunk stability and movement (Moseley & Hodges, 2005; Stackhouse *et al.,* 2005; Urquhart *et al*., 2005; Unger 2011), it is therefore not clear how this variant result of RA may impact on the stability and maintenance of posture in individuals with STCP.

The RA muscle showed a pennation angle of 0°, which implies that this muscle is non-pennated. There are no data in the literature with which to compare the PA of RA. However, gross morphological observation of dissected cadaveric parts showed the striped nature of this muscle to confirm its longitudinally orientated fibres which may confirm it to be non-pennate and with a PA of 0°. Different studies have shown that non-pennate muscles generate sufficient force in comparison to pennate muscles (Woittiez *et al*., 1984, Binzoni *et al.,* 2001, Shortland *et al.,* 2002, Wakahara *et al.,* 2012). This could apply to the RA as opposed to the other abdominal muscles which show weak pennation (PA = 0.5° to 2.8°).

The EMG results of the RA in the STCP group at resting state were also significantly lower ($p < 0.001$) than for the rest of the abdominal muscles. The change in EMG activity that signifies muscle strength was much greater in the RA than the other muscles. Stackhouse *et al.* (2005) noted that neuromuscular electrical activation may be advantageous over voluntary contraction exercises. The ultrastructural revelations of the abdominal muscles could be considered in choosing rehabilitation therapies.

Other descriptive characteristics of the RA of the STCP group that are at variance with the rest of the abdominal muscles include:

- A negative correlation with PCI,
- Lack of correlation a correlation between the EMG resting results at rest and the other muscles upon contraction (*rho* = -0.08 to -0.06), and
- FL coinciding with inter-sarcomeric length as there was no PA from which to calculate FL.

As to whether these variances in the results of RA compared with the other abdominal muscles in individuals with STCP in the present study represent measurement errors or

inherent differences requires further investigation. The implications of the differences seen are discussed subsequently under the respective parameters.

5.9 The relationship between gross motor function measure (GMFM), muscle activity and disability levels

There was no association between either the gross motor function measure (GMFM) and muscle parameters or between GMFM and muscle activity (EMG score). Similar observations were made by Zwaan *et al.* (2012) who reported of a lack of correlation between GMFM and EMG activity of the lower limb muscles in 39 children with STCP and TD. Additionally, neither the changes in muscle thickness nor the changes in the recruitment patterns from rest to active state correlated with GMFM. Despite evidence from the results to suggest that the changes in muscle thickness as well as changes in the frequency of recruitment of muscle fibres from the resting to active states characterise muscle strength, GMFM score did not correlate with these changes either. Although Ohata *et al. (*2008) suggested that quantifying the change in muscle thickness may be a useful tool in the determination of gross motor function, evidence from the current study appears that the link between spasticity and therefore, indirectly with the impairment in function and the changes in muscle thickness is lacking. It is therefore most likely that GMFM as a functional outcome tool is not responsive to changes in MAP's and the recruitment of motor units. Similar observations were made by Palisano *et al.* (2000) when correlating GMFM with the age of participants which resulted in these investigators suggesting that the GMFM as a tool may not be predictive of the strength and the ability of a child to perform daily activities. There have not yet been any reports relating GMFM directly to the ultrastructural parameters of individuals with STCP. The strength of a muscle, however, has been shown to correlate highly with gross motor function in ambulatory children with spastic diplegia (Ross & Engsberg, 2002). Deductions from this study seems to point to the fact that although a muscle may appear active, the gross motor function of an individual in the performance of daily tasks may be as a result of the collective effort of several groups of muscles and may not necessarily depend solely on a single group of specially trained muscles. This position could be explained better with the results of the RA in the STCP group showing optimum activity with regards to all the investigations carried out but lacking a correlation between the GMFM test and the changes there are in muscle thickness and EMG scores. It is not clear whether the lack of correlation between GMFM test and MAP's as well as with EMG activity

in individual muscle groups may impact on the intervention programmes for the children with STCP, but it appears that rehabilitation treatments solely aimed at reducing impairment of targeted muscles may not be particularly effective. The gross motor function of a child in general may be impaired by weakness and / or lack of recruitment of motor units, however, the GMFM test does not seem to be sensitive enough to detect these malfunctions at the level of individual muscles. The performance of daily tasks such as walking involves the integration of all muscles groups of the bony pelvis. A possible reduction in the tone of all identified spastic muscles must be of prime consideration by therapists.

However, the GMFM scores discriminated between the four disability levels (GMFCS Levels I – IV) that were examined. The current results indicated that the mildly affected participants classified as GMFCS Level I, performed best on this functional scale. With regard to impairment, participants in the study who were grouped in this category (I) are more closely related to TD individuals than children from GMFCS Level IV, who are severely affected by the condition and thus scored poorly with the GMFM test. Similar observations were made in the study of Himmelmann and co-workers (2007). The maximum, minimum and median scores of the children from GMFCS Level II were the most striking (Figure 25) with a large overlap between the individuals at level II and the 95% confidence interval limits of the scores of individuals from GMFCS III. In the current study there was more overlap in the gross motor function measure of levels II and III than seen between Levels I and II. In the study of Palisano and co-workers, an exception to the GMFM scores of children classified in level II was also reported in which participants in the GMFCS Level II category failed to achieve the expected scores at a given age (Palisano *et al.,* 2000; Wood & Rosebaum, 2000). With individuals in the GMFCS Level II, it is most probable that incorrect classifications have occurred for children in this particular group. This may be the case since there are subtle characteristics that distinguish participants from this category from those in either GMFCS Levels I or III. The findings of the GMFM test in the present study show that there is a correlation between the gross motor function and spasticity expressed as GMFCS Levels. It seems that the existence of an association between the GMFM test and the degree of disability supports the view that spasticity may contribute to motor impairment. The findings of the GMFM test in the current study in relation to the different disability levels are similar to the results of the study of Bartlett *et al*. (2010).

5.10 Hemiplegia

Data from individuals with spastic hemiplegia in this study showed that the muscle thickness of the unaffected side indicated patterns that are similar to the results from the TD group, while the affected side indicated patterns as seen in the diplegic group (Tables 41 & 42 and Figure 28). This suggests that the abdominal muscles are also unilaterally affected in children with spastic hemiplegia in a similar fashion to the limb muscles. The unaffected side of children with spastic hemiplegia showed similar changes from resting to active states as children with TD in the thickness of all the muscles whereas the affected side showed similar responses to what is seen in the STCP group. For the EO, IO (and probable the TrA which was not tested) the EMG changes were significantly greater and positive on the unaffected side. The results of the hemiplegic individuals from the current study are similar to the report by Gorter *et al*. (2004) in that the impairment of body structures in individuals diagnosed with spastic hemiplegia is not limited only to the limb musculature.

5.11 Reflections – strengths, weaknesses and new research questions that emerge

The amount of connective tissue relative to the contractile component in these morphologically distinct muscles was not investigated in this study but the role of the ratio between the connective tissue and muscle, especially in the STCP group with respect to the differences relating to contractile or non-contractile tissue, should not be overlooked. What has not yet been documented is the extent to which the connective tissue may influence muscle activity and also the degree to which the RA on the one side and the EO, IO and TrA on the other side become adapted in their activity and contraction under pathological conditions. This interplay between muscle and connective tissue components must be the subject of intense investigation prior to the adoption of any guidelines on the practice of musculoskeletal rehabilitation. One advantage of the present study is the exploration of the basic functional biology of the muscle that seems to link morphological structures to the theory and the practice of the management of cases involving STCP.

The current study also correlated the alterations in thickness of individuals with STCP to the possible onset of biomechanical mechanisms in the abdominal muscles. The hormonal influences on muscle function were not explored in this study. Suggestions about the interplay between contractile and non-contractile tissues, however, must not be taken to imply causality between some of these predictive mechanisms and the incidence of STCP.

The current study is largely descriptive and subjected to several limitations such as generalisability of the sample, therefore only further investigations could provide a deeper understanding in this field.

It is worth mentioning here that to the best of knowledge of this investigator no such work has been conducted on the abdominal muscles in individuals with STCP and it is therefore challenging to relate the results of the abdominal parameters from the current study to another research project.

One of the challenges encountered in the execution of this study is that there are relatively few studies on the abdominal muscles in the literature. The few publications found using the search strategy were mainly on healthy adults, thereby rendering them incomparable since the current study focused on children and adolescents with STCP. As a result most of the hypotheses on which this study was designed had been based on observations from lower limb muscles in children with STCP. For example, it is stated that muscle thickness represents muscle strength in the lower limb. Although muscle strength was not measured directly in this study, the assumption made in the current study is that this might be the case following reports from the lower limb. This is a setback to the validity for a study such as this one which seems to be the first to quantify all muscle parameters in the abdominal muscles of children and adolescents. Therefore, a further investigation that would need to be done in order for some of the findings in the present study to be generalised may be whether the thickness of abdominal muscles is a reliable indicator of muscle strength as suggested for limb muscles.

Similarly, further investigation is required on the functional implication of the heterogeneous nature of pennation in the abdominal muscles. The mechanism by which the condition of STCP could confer mosaicism or a hybrid nature to a particular muscle within a muscle group was also beyond the scope of this study. The implication of this result with its underlying functional relationships, could only be explained with the influx of information on the ultrastructural aspect of individual muscles within other muscle groups such as the triceps brachii, quadriceps femoris, hamstrings, triceps surae and intrinsic back, hand / foot muscles in individuals with STCP.

The functional relationship between the thin abdominal muscles and the cellular consumption of energy in order to contract for the provision of stability to the strong and rigid bony pelvis was inconclusive from this study. The responsiveness of the test for PCI as an outcome

measure of MAP's and EMG activity of the abdominal muscles could only become relevant when the PCI scores are analysed alongside the fibre type, which was beyond the scope of this study and would therefore require further investigation.

5.12 Reliability of measuring instruments

The results were comparable with other studies and most of them made logical sense in hindsight. The US and EMG were reliable and valid based on a range of tests that were used as shown in Appendix C. The descriptions and discussion on the relialibility and validity of the test instruments as well as the results have already been presented in section 3.3.9. However FL yielded poor results and the use of the formula as described in literature is not recommended for abdominal muscles.

5.13 Limitations of the study

The calculation and derivation of fibre length is the major limitation to the study. Although inter- and intra-class co-efficient showed fair repeatability and reliability of this muscle parameter, the scores obtained appear impractical especially when compared to data from other parts of the body.

While sample size was adequate, the demographic representation of STCP cases in the subgroup analysis performed on tests such as GMFM, GMFCS and PCI may not have been large enough to provide sufficient statistical power for the results in terms of generalisability.

The fact that in this study the children were not classified into their GMFCS Levels by the researcher was another setback because the categorisation of the participants into disability levels was extracted from the personal data of the learners in their respective schools, based on the criteria from the health care providers. In this regard this was a reliance on the judgment of other people and may be considered as lacking scientific evidence.

There is a potential of misdiagnosis of CP (the cases used in the study) in general, since none of the participants underwent imaging in the craniospinal axis.

Arguably, the strength of the individual muscles were inferred from the electrical activity in the muscle fibres as evaluated by the EMG scores. This inference may be incorrect on the basis that from a practical point of view, technical issues such as electrode placement could give varied EMG scores.

Regarding the language of communication, English was used because the PI was unable to communicate in isiXhosa and Afrikaans. Compliance to instructions by participants especially with regard to movement of body parts, is key to the realisation of good results. The inability of both the PI and participants to have a common medium of communication apart from the English language could have an influence on the overall results.

Chapter 6 Conclusion and recommendations

6.1 Introduction

Individuals with STCP show alterations in their locomotor apparatus at some stage in their life (Lampe *et al.,* 2006; Gao *et al*., 2011). These locomotor apparatus include skeletal muscles, tendons, ligaments and joints (Andersen & Mattsson, 2001; Moreau *et al.,* 2010). Quantifying the exact anatomical structures that have been transformed has been a source of concern to researchers for decades (Damiano *et al.,* 2001; Elder *et al*., 2003). However, the alterations of these structures of locomotion have often been associated with difficulty in walking and / or the inability to maintain a steady gait (Gao *et al*., 2011; Ko *et al*., 2013).

Limb muscles have been the target of research in individuals with STCP with the accompanying gait and posture related problems. Weak abdominal muscles have been reported to have the ability to negatively affect the gait, cadence and posture of individual with STCP (Ohata *et al*., 2008). This study investigated the ultrastructure of the abdominal muscles in relation to function. Knowledge of the changes taking place in the architectural parameters of abdominal muscle between the resting and active states may be important in the understanding of the transformations or malformations taking place in these muscles with respect to function at the bony pelvis. The general aim of this study was to determine whether changes in MAP's of the abdominal muscle relate to poor posture and the imbalance of the trunk. For this purpose, the changes in MAP's in individuals with STCP were compared across the various disability levels and also with age-matched TD individuals. This appears to be the first study that relates MAP's of abdominal muscles to gross motor function, and therefore it may contribute to a greater understanding of these muscles with respect to locomotion and the provision of stability.

6.2 Conclusion on the specific measurable themes

Based on the evidence provided above, the specific objectives as described in section 1.11.1 of page 10 in this study may be answered as follows:

- ***To validate ultrasonographic measurements of abdominal muscle thickness during resting and contracted states in children with STCP and in children from the typically developing (TD) group.***

There has been suggestion in the literature without empirical evidence that the change in muscle thickness from the resting to active state represents the most reliable MAP's in predicting muscle activity and strength (Damiano *et al.,* 2000; Hodges *et al.,* 2005; Goh *et al.,* 2006; Ohata *et al*., 2008). The work of Unger (2011) showed differences in thickness between the abdominal muscles of children with STCP and TD individuals, but was unable to correlate these changes in thickness between the two groups to recruitment of fibre patterns and muscle activity. The present study shows that these changes in thickness are not only measurable using ultrasound techniques but could also be linked to muscle activity.

- ***To determine whether there is any significant difference in muscle fibre alignment / orientation (pennation angle) during resting and contracted states among children and adolescents with STCP and those from the TD group.***

Muscle thickness, muscle fibre length and pennation angle have often been identified as those muscle architectural parameters that determine the amount of force generated by a muscle (Abe *et al.,* 1998; Lieber & Friden, 2000; Ohata *et al.,* 2008). Most reports on PA of the abdominal muscles have been inferences from the investigations on MAP's of the lower limb. Consequently all four abdominal muscles have been classified as parallel muscles (McMeeken *et al.,* 2004). However, with regards to pennation, the evidence from this study indicated that abdominal muscles as a group may represent a transition from being poorly pennated as seen in the EO, IO and TrA to non-pennated in the RA of both groups. This is the first study to highlight the hybrid nature of abdominal muscles with regard to the orientation of the muscle fibres.

Although small pennation angles (PA) were observed for the external oblique (EO), internal oblique (IO) and transversus abdominis (TrA) in both groups, the changes in PA on contraction showed a significant difference ($p < 0.01$) between the two groups. In the STCP group, the pennation angles of EO, IO and TrA either remained unchanged or decreased in

angulation on contraction, whereas the PA of these muscles in TD individuals increased from resting to active state. Although these angulations indicated that the EO, IO and TrA muscles are weakly pennated muscles, this does not mean that that they are non-pennated, as is the case with the RA. This is the first study to investigate all three MAP's, including the PA of the abdominal muscles in individuals with STCP. The observation that RA in both groups is similar with the attachment of the fibres in the longitudinal direction to the line of pull is important. This may mean that although RA muscle in the STCP group showed similar characteristics to those of TD individuals, the observation that the RA is a non-pennated muscle makes it easy to infer that the generation of force by the RA may not be sufficient to take over the activities of the much affected EO, IO and TrA, in stabilising the bony pelvis.

The study answered the above objective in the following way:

- Differences exist in the changes in PA from resting to active state in both groups for the EO, IO and TrA,
- The RA in both groups showed similar characteristics with respect to pennation angle.

- ***To determine which of these MAP's - muscle thickness, pennation angle and fibre length - is most predictive of muscle activity / strength***.

The consistency and the reliability of the results of muscle thickness in both groups during the resting and active states may lend support to the conclusion that muscle thickness may be the most likely parameter to predict muscle activity. The changes in muscle thickness on contraction were closely related to the patterns of fibre recruitment in both groups as evidenced by the changes in EMG frequency from the resting state to the contracted state. Based on the observation of large pennation angles (PA) in the lower limb, some researchers have concluded that PA is related to muscle activity in much the same way as is muscle thickness (Kawakami *et al.,* 2006; Iwanuma *et al*., 2011; Wakahara *et al*., 2012). However, evidence from this study indicated that although PA is fairly consistent in both groups, the values are relatively small when compared to results from lower limbs that any correlation between the PA and muscle activity / strength of the abdominal muscles may be considered weak and without any therapeutic implication.

Similarly, the results of fibre length in both groups were inconsistent and lack any correlation with muscle activity. The state of abdominal muscle activity and or strength could not be

inferred mainly from an evaluation of fibre length for the implementation of any management procedure.

The study seems to have answered this objective using the evidence provided that even though muscle thickness, pennation angle and fibre length have been documented as a predictor of muscle strength / activity, with regard to the abdominal muscles, thickness and the changes associated with that thickness on contraction may be regarded as the most reliable and predictive of muscle performance.

- ***To determine whether there is any significant difference in macroscopic muscle parameters (MAP's) - muscle thickness, fibre length and pennation angle in children with STCP across the different levels of CP i.e (Gross Motor Function Classification Scale [GMFCS I, II, III & IV]).***

The study showed no association between MAP's and the disability levels of participants. No MAP's appear to be adversely affected across the GMFCS levels. However, a correlation of the measure of functional ability across the various disability groups indicated that

As has been found in the rehabilitation literature, it is apparent that impairment on the level of body structure and function does not necessarily translate into function. However, the variability between the score of the STCP might be small and therefore, as all are impaired with regard to the MAP's tested and all are functionally disabled, there is not much variance between the scores on the MAP's and the GMFM. It seems as if the child either has abnormal muscle parameters and is functionally impaired, or does not have impairments and is functionally able.

- ***To determine whether there is any significant difference in surface EMG activity in the abdominal muscles during resting and contracted states of children and adolescents with STCP and those from the TD group.***

Evidence from this study reveals that there was a significant difference ($p < 0.001$) between the frequency of the recruitment patterns of the muscle fibres in both groups during resting and active states. The changes in EMG activity between the resting and contracted states of the two groups were also significantly different for the EO and IO muscles but no difference was observed for the RA of both groups. The deductions made from these differences in EMG activity between individuals with STCP and TD children are that the onset of STCP may be accompanied by an accentuated neuromuscular activity even at rest to such a level

whereby during contraction, the abdominal muscles lack the capacity to recruit more motor units.

- ***To determine how MAP's relate to function in different age groups of children with STCP and the different ambulatory groups (GMFCS levels I, II and III) by assessing the gross motor function measure (GMFM) among the three ambulatory groups of STCP.***

The findings from this study based on this specific objective revealed that the muscle parameters are linearly related to the age of the participants. With regard to the age, disability levels and gross motor function of the participants, the findings may conclude that a strong correlation exists between functional ability and level of disability (GMFCS levels). However, deductions from the study also reveal that, although the GMFM test discriminated fairly among the GMFCS levels, this outcome measure may lack the responsiveness to changes in muscle parameters. The GMFM test may not be a useful tool for the evaluation of the degree of transformation taking place in a particular group of muscle.

- ***To determine whether there is any significant difference in energy consumption as measured by means of the physiological cost index (PCI) and whether there is any correlation between the PCI and architectural parameters of muscles between the STCP and TD groups.***

Energy consumption as evaluated through the PCI measure in this study indicated that more energy was consumed in the performance of daily activity such as walking in individuals with STCP than was used up by TD children. It appears from these findings that the condition of STCP increases the consumption of energy during the performance of daily tasks, therefore it could be deduced that spasticity may be indirectly related to low threshold of fatigue. However, the PCI test showed no association with the muscle architectural parameters in both groups. The changes in the internal activities of various muscle fibres in the individual muscle groups failed to correspond to the PCI scores. In conclusion the study may have answered this specific objective in two ways:

(i) Significant difference exist between the STCP and TD groups by way of PCI scores, and

(ii) No correlation is found between PCI and MAP's in both groups.

In summary and with reference to the broad aims of this study as outlined in section 1.1 of page 2 and recaptured as follows:

- ***Identifying whether abdominal muscles undergo transformation in children with CP,***
- ***Establishing the nature of any such structural changes that may occur, and***
- ***Determining whether these changes impact on function.***

The study has provided evidence that most of the abdominal muscles of children and adolescents with STCP when compared to TD individuals showed changes in architecture. The rectus abdominis muscle, however, indicated no change in muscle parameters in individuals with STCP when compared with TD individuals.

The study also showed that when at rest the EO, IO and TrA were thicker than on contraction. It could also be established from this study that these muscles showed a decrease in pennation angle and also in fibre length on contraction. The RA of individuals with STCP showed no difference in structure when compared with TD individuals.

The correlation between these changes on muscle function and on the performance of daily activity was not clear. However, compared with muscles of individuals from the TD group, these changes in muscle architecture in individuals with STCP appear to impact adversely on the bony pelvis.

6.3 Significance of study

This study may add further information to the field of cerebral palsy and changes that take place in abdominal muscles with the occurrence of spastic type cerebral palsy, which impact on rehabilitation strategies. Some of the findings and suggestions listed below may add new knowledge to the field of muscle architecture and cerebral palsy in general:

- Ultrasound imaging is a fast, reliable and easy to measure muscle thickness even with novice researchers and practitioners. The study validates the use of ultrasound as a reliable tool in quantifying muscle thickness.
- Although the MAP's of the limb muscles have been documented, this study correlates well to the findings of Unger (2011) and together with that study, describes the abdominal muscle parameters of both children with STCP and TD children for the first time.
- Spasticity seen in the abdominal muscles may not represent a lack of neuromuscular activity in the muscle fibres, as shown by the increased activity of motor unit during the resting stage in the oblique abdominal muscles. Procedures that are capable of

reducing the increased muscle tone may be essential prior to strengthening these muscles.

- Abdominal muscles exist as a heterogeneous group along the anterior segment of the trunk. Each of these muscles shows unique sets of characteristics with respect to the generation of forces as well as the provision of stability for the bony pelvis. A thorough understanding may be required about their involvement in the maintenance of stability and adequate posture with respect to the management of the mal-alignment of the trunk in individuals with STCP.
- The anterolateral abdominal muscles (EO, IO and TrA) have poorly pennated muscle bellies which become virtually like non-pennated muscles on contraction while the RA, which is sagittally located, was found to behave as a typically non-pennated muscle during resting and active states.
- Functional outcome measures used in clinical practice to evaluate muscle characteristics may not correlate closely with the true anatomical and physiological states of the various abdominal muscles.

6.4 Recommendations for future research

Further investigations into the nature of muscle structure are important in the provision of information for use in forecasting other disabilities and limitations in activity associated with spastic type cerebral palsy. The present study, which explored the link between theory and clinical practice, provides the following recommendations for future studies.

Further studies on the basic structure, function and neuromuscular activities of the abdominal muscles as well as the intrinsic low back muscles in individuals with STCP, are essential for the understanding of the maintenance of stability through the bony pelvis by these core muscles. The maintenance of posture and stability are equally important to locomotor activities if the long term complications of structures are to be avoided in cases involving STCP. A paradigm shift of research on cerebral palsy towards the basic structure and function of all the muscle groups involved in the provision of balance to the bony pelvis may deepen the knowledge and understanding of STCP and its management. In future studies, kinematic analysis of body posture, specifically of the pelvic tilt should be included.

In addition to the non-invasive use of ultrasonography to investigate the structure of abdominal muscles, there may be a need for biochemical analysis of these muscles in order to

determine the composition of fibre types. This may provide more insight into the structure and function of abdominal muscles and thus deepen knowledge on the role played by these muscles at the bony pelvis.

6.5 Recommendations for practice

Of relevance to practitioners, the oblique abdominal muscles and most likely the transversus abdominis muscle were observed to have increased tone at rest in individuals with STCP. This leads to the following questions that may be asked. How can tone in these muscles be reduced prior to strengthening them, if they are to exert any meaningful force at the bony pelvis? The rectus abdominis (RA) muscle appears to be relatively unaffected by STCP. The question of how to maximally activate the lateral muscles and reduce the reliance on RA needs to be addressed within the clinic set-up. Is it possible to inhibit the action of RA while simultaneously activating the lateral abdominal muscles and train the selective muscle control that is the aim of some forms of physical therapy? On the other hand, given that the RA is parasagittally located with the adjacent abdominal muscles rather being affected by STCP, should the perceived optimal activity in the RA be exploited in rehabilitation regimens in order to become beneficial to trunk stability?

6.6 Conclusion

Although few direct relationships between function and muscle parameters were found, the large differences between the two groups in muscle activation ability indicate that the abdominal muscles are indeed severely affected by cerebral palsy. Many questions have been raised by this study and it is clear that a greater understanding of the structure and function of these muscles is necessary in order to facilitate the development of more effective rehabilitation interventions. The rehabilitation techniques will need to target both the impairments, specifically the poor activation of muscles and the functional limitations, including gross motor function and increased energy usage during gait. In this way, children with cerebral palsy may be helped to reach their full functional potential, regardless of their level of functional limitation.

Chapter 7 References

Abe T, Brechue WF, Fujita S, Brown JB. Gender differences in FFM accumulation and architechural characteristics of muscles. Med. Sci. Sports Exercise. 1998; 30: 1066–1070

Abe T, Brown JB. Breche WF. Architectural characteristics of skeletal muscle in black and white college football players. Med. Sci. Sports Exercise. 1999; 31: 1448-1452.

Acland RD. The inguinal ligament and its lateral attachments: correcting an anatomical error. Clinical Anatomy. 2008; 21: 55-61.

Adcock CJ. Sample size determination: a review. J. Royal Sta. Soc. 1997; 46 (2): 261-283.

Aggeloussis N, Giannakou E, Albracht K, Arampatzis A. Reproducibility of fascicle length and pennation angle of gastrocnemius medialis in human gait in vivo. Gait & Posture. 2010; 31: 73-77.

Aiona MD. The ambulatory child with cerebral palsy. In Richards BS. Orthopaedic knowledge updates pediatrics. Rosemont, III: American Academy of Orthopaedic Surgeons. 1996; 19-27.

Allen PE, Jenkinson A, Stephens MM, O'Brien T. Abnormalities in the uninvolved limb in children with spastic hemiplegia: the effect of actual and functional leg-length discrepancy. J Pediatr. Orthop. 2000; 20: 88-92.

Alston F, Britz C, Jelsma J. An investigation into the inter-rater reliability of ultrasound imaging of abdominal muscles in adults. Journal of Community and Health Sciences. 2009; 4: 1-12.

Altman DG, Schulz K F, Moher D, Egger M, Davidoff F, Elbourne D, Gotzsche PC, Lang T. The Revised CONSORT Statement for Reporting Randomized Trials: Explanation and Elaboration. Annals of Internal Medicine. 2001; 134 (8): 663-683.

Altman DG, Bland JM. Standard deviations and standard errors. BMJ 2005; 331: 903.

Andersen GL, Irgens LM, Haagaas I, Skranes JS, Meberg AE, Vik T. Cerebral palsy in Norway: prevalence, subtypes and severity (2008). Eur J Paediatr Neurol 12 (1): 4–13.

Andersson C, Mattsson E. Adults with cerebral palsy: a survey describing problems, needs and resources with emphasis on locomotion. Dev. Med Child Neurol. 2001; 43: 76–82.

Anterior view of abdominal muscles. http://www.yorku.ca/earmstro/images. Date accessed: 30/05/2013. *Sourced* from Anatomy of the human body, by Henry Gray. 20th ed.

Anterior pelvic tilt. http://www.floota.com/imag. Date accessed: 30/05/2013.

Aubert EJ. Motor development in the normal child. In Tecklin JS; ed. Pediatric Physical Therapy 4th ed. Wolters Kluwer; Lippincott Willians & Wilkins, 2008: 17–64.

Avery LM, Russell DJ, Raina PS, Walter SD, Rosenbaum PL. Rasch analysis of the gross motor function measure: validating the assumptions of the Rasch Model to create an interval level measure. Arch. Phys. Med. Rehabil. 2003; 84: 697-705.

Axler CT, McGill SM. Low back loads over a variety of abdominal exercises: searching for the safest abdominal challenge. Med Sci Sports Exerc. 1997;29:804-811.

Azizi E, Brainerd E. Architectural gear ratio and muscle fibre strain homogeneity in segmented musculature. J. Exp. Zool. 2007; 307A: 145-155.

Bache CE, Selber P, Graham HK. The management of spastic diplegia. Curr Orthop 2003; 17: 88–104.

Bakke M, Tuxen A, Vilmann P, Jensen BR, Vilmann A, Toft M. Ultrasound image of masseter muscle related to force, electromyography, fascial morphology and occlusion factors Scand. J Dent. Res. 1992; 100: 164–171.

Bandholm T, Magnusson P, Jensen BR, Sonne-Holma S: Dorsiflexor muscle-group thickness in children with cerebral palsy: Relation to cross-sectional area. NeuroRehabilitation 2009; 24: 299–306.

Barber L, Barrett R, Lichtwark G. Medial gastrocnemius muscle fascicle active torque-length and Achilles tendon properties in young adults with spastic cerebral palsy. J. Biomech 2012; 45: 2526–2530.

Barber L, Hastings-Ison T, Baker R, Barrett R, Lichtwark G. Medial gastrocnemius volume and fascicle length in children aged 2 to 5 years with cerebral palsy. Dev. Med. Child Neurol. 2011; 53: 543-548.

Barrett RS, Lichtwark GA: Gross muscle morphology and structure in spastic cerebral palsy: a systematic review. Developmental Medicine & Child Neurology 2010; 52: 794–804.

Bartlett DJ, Hanna SEAvery L, Stevenson RD, Galuppi B. Correlates of decline in gross motor capacity in adolescents with cerebral palsy in the gross motor function classification system levels III to V: an exploratory study. Dev. Med. Child Neurol. 2010; 52: e155-e160.

Bax M, Goldstein M, Rosenbaum P et al., Proposed definition and classification of cerebral palsy, April 2005. Dev.Med.Child Neurol. 2005; 47: 571-576.

Beckung E, Hagberg G. Neuroimpairments and activity limitations and participation restrictions in children with cerebral palsy. Dev. Med. Child Neurol. 2002; 44: 309-316.

Benard MR, Becher JG, Harlaar J, Huijing PA, Jaspers RT. Anatomical information is needed in ultrasound imaging of muscle to avoid potentially substantial errors in measurement of muscle geometry. Muscle Nerve 2009; 39: 652-665.

Bergmark A. Mechanical stability of human lumbar spine: a study in mechanical engineering. Acta Orthop. Scan. 1989; 230 (suppl): 1 – 54.

Bertoti DB. Effect of therapeutic horseback riding on posture in children with cerebral palsy. Phys.Ther. 1988; 68:1505-1512.

Binzoni T, Bianchi S, Hanquinet S, Kaelin A, Sayegh Y, Dumont M, Jequier S. Human gastrocnemius medialis pennation angle as a function of age: from newborn to elderly. J. Physiol Anthropol. Appl. Human Sci. 2001; 20: 293–298.

Blair E, Stanley FJ. Issues in the classification and epidemiology of cerebral palsy. Mental Retard. Dev. EDisabil. Res. Rev. 2001; 3: 184-193.

Blazevich AJ. Effects of physical training and detraining, immobilisation, growth and aging on human fascicle geometry. J. Sports Med. 2006; 36 (12): 1003-1017.

Bolek J. The Role of Surface Electromyography in the Restoration of Motor Function. Biofeedback. 2007; (35), 1: 23–26.

Bony pelvis picture. http://www.urogynecology.co.il/im. Date accessed: 30/05/2013

Bony pelvis positions. http://www.floota.com/imag. Date accessed: 30/05/2013.

Bottos M, Feliciangeli A, Sciuto L, Gericke C, Vianello A. Functional status of adults with cerebral palsy and implications for treatment of children. Dev Med Child Neurol 2001; 43: 516–528.

Bowen TR, Lennon N, Castagno MS, Miller F, Richards J: Variability of energy-consumption measures in children with cerebral palsy. J. Pediatr Orthop. 1998; 18: 738–742.

Boyett MR, Frampton JE, Kirby MS. The length, width and volume of isolated rat and ferret ventricular myocytes during twitch contraction and changes in osmotic strength. Exp. Physiol. 1991; 76: 259–270.

Brainerd E, Azizi E. Muscle fibre angle, segment bulging and architectural gear ratio in segmental musculature. J. Exp. Biol. 2005; 208: 3249-3261.

Brener ND, McManus T, Galuska DA, Lowry R, Wechsler H. Reliability and validity of self-reported height and weight among High school students. J. Adolescent Health, 2003; 32: 281–287.

Brogren E, Hadders-Algra M, Forssberg H. Postural control in children with spastic diplegia: muscle activity during perturbation in sitting. Dev. Med. & Child Neurol. 1996; 38: 379–388.

Brogren E, Hadders-Algra M, Forssberg H. Postural control in sitting children with cerebral palsy. Neurosci.Biobehav.Rev. 1998;22:591-6.

Brogren E, Forssberg H. Hadders-Algra M. Influence of two different stting positions on postural adjustment in children with spatic diplegia. Dev. Med & Child Neurol. 2001; 43: 534–546.

Brooks SV, Faulkner JA. Contractile properties of muscles from young, adult and aged mice. Journal of Physiology 1988; 404;71–82.

Bunce SM, Moore AP, Hough AD. M-mode ultrasound, a reliable measure of transversus abdominis thickness? Clin. Biomech (Bristol Avon) 2002; 17: 315 – 317.

Burtner PA, Qualls C, Woollacott MH. Muscle activation characteristics of stance balance control in children with spastic cerebral palsy. Gait & Posture 1998; 8: 163-174.

Butler PB. A preliminary report on the effectiveness of trunk targeting in achieving independent sitting balance in children with cerebral palsy. Clin.Rehabil. 1998;12:281-293.

Buyken AE, Hahn S, Kroke A. Differences between recumbent length and stature measurement in groups of 2- and 3- year- old children and its relevance for use of European body mass index references. Int. J. Obes. 2005; 29: 24–28.

Campbell SK. Framework for the measurement of neurologic impairment and disability. In: Lister MJ, editor. Contemporary management of motor control problems. Proceedings of the II step conference. Alexandria (VA): Foundation for Physical Therapy; 1991; 146-147.

Canale ST. Cambell's Operative Orthopaedics. 1998; 154-159: 9th Ed. Mosby Publ. St. Louis.

Chapman MW, Madison M. Operative Orthopaedics. 1988; 279-283: 2nd Ed. Lippincott Company. Philadelphia.

Chapman AR, Vicenzino B, Blanch P, Hodges PW. Patterns of leg muscle recruitment vary between novice and highly trained cyclists. J. Electromyogr. & Kinesiol. 2008; 18 (3): 359-371.

Cholewicki J, Panjabi MM, Khachatryan A. Stabilising function of trunk flexor-extensor muscles around a neutral spine posture. Spine 1997; 22: 2207-2212.

Cholewicki J. Simons APD, Radebold A. Effects of external trunk loads on lumbar stability. J. Biomech. 2000; 33 (11): 1377–1385.

Clark DJ, Patten C, Reid KF, Carabello RJ, Phillips EM, Fiedling RA. Muscle Performance and Physical Function are Associated with Voluntary Rate Neuromuscular Activation in Older Adults. J. Gerontol. A. Biol. Sci. Med. Sci. 2011 (Jan 66A1): 115–121.

Couper J. Prevalence of childhood disability in rural Kwazul-Natal. S.Afri. Med. J. 2002; 92 (7): 549–552. Abstract.

Cram JR, Kasman GS, Wolf SL. Clinical Application in surface electromyography. 1998. Alexandria: Aspen Publications.

Cresswell AG, Grundstrom H, Thorstensson A. Observations on intra-abdominal pressure and patterns of abdominal intra muscular activity in man. Acta Physiologica Scandinavica. 1992; 144: 409–418.

Critchley DJ. Instructing pelvic floor contraction facilitates TrA contraction during low abdominal hollowing. Physiother Res. Int. 2002; 7: 66–75.

Critchley DJ. Coutts FJ. Abdominal muscle function in chronic low-back pain patients: measurements with real-time ultrasound scanning. Physiotherapy 2002; 86: 322–332.

Crompton J, Galea MP, Phillips B. Hand-held dynamometry for muscle strength measurement in children with cerebral palsy. Dev. Med. Child Neurol. 2007; 49: 106-111.

Daly LE, Bourke GJ, McGilvray J: Interpretation and Uses of Medical Statistics. 1991; 425-427: 4th ed. Blackwell Scientific Publication, London.

Damiano DL. Reviewing muscle cocontraction: is it a developmental, pathological, or motor control issue. Phys Occup Ther Pediatr 1993; 12: 3-20.

Damiano DL, Martellota TL, Sullivan DJ, Granata KP, Abel MF. Muscle force production and functional performance in spastic cerebral palsy: relationship of cocontraction. Arch Phys Med Rehabil. 2000; 81: 895–900.

Damiano DL. Activity, activity, activity: rethinking our physical therapy approach to cerebral palsy. Phys Ther 2006; 86: 1534–40.

Damiano DL, Moreau N. Muscle thickness reflects activity in CP but how well does it represent strength? Dev Med Child Neurol 2008; 50: 88.

Dankaerts W, O'Sullivan PB, Burnett AF, Straker LM, Danneels LA. Reliability of EMG measurements for trunk muscles during maximal and submaximal voluntary isometric contractions in healthy controls and CLBP patients. J. Electromyogr. & Kinesiol. 2004; 14: 333-342.

Dario F, Merletti R, Enoka RM. The extraction of neural strategies from surface EMG. J. Appl. Physiol. 2004; 96: 1486-1495.

Davies MF, Worden K, Clawson D, Meaney J, Duncan B. Confirmatory factor analysis in osteopathic medicine: fascial and spinal motion restriction as correlates of muscle spasticity in children with cerebral palsy. J. Am. Osteopath Assoc. 2007; 107226– 107232.

Delagi EF, Perotto A. Anatomic guide for the electromyographer: the limbs, 1980; 46-50: 2nd ed. Sringfield Publ.

Delp SL. New research centre to study basis of mobility disorders using powerful 3-D simulation patients' movements. http: //mednews.stanford.edu/Jan 2011.

Deluca PA, Gait analysis in the treatment of ambulatory child with cerebral palsy. Clin. Orthop. 1991; 264: 65-74.

Deluca PA. The musculoskeletal management of children with cerebral palsy. Pediatr Clin North Am 1996; 43: 1135-1150.

DeTroyer A. Mechanical role of the abdominal muscles in relation to posture. J. Respiratory Physiology. 1983; 53: 341–353.

DeTroyer A, Estenne M, Ninane V, VanGansbeke D, Gorini M. transversus abdominis muscle function in humans. Journal of Applied Physiology. 1990; 68: 1010 – 1016.

D'hooge J, Heimdal A, Jamal F, Kukulski T, Bijnens B, Rademakers F, Hatle L, Suestens P, Sutherland GR. Regional strain and strain rate measurements by cardiac ultrasound: principles, implementation and limitations. Eur. J. Echocardiogr. 2000; 1 (3): 154-170.

Dolk H, Pattenden S, Johnson A. Cerebral palsy, low birthweight and socio-economic deprivation:inequalities in a major cause of childhood disability. Pediatric and Pernatal Epidemiology 2001: 15; 359–363.

Dolk H, Pattenden S, Bonellie S, Colver A, King A, Kurnczuk JJ, Parker J, Platt MJ, Surnam G. Socio-economic inequalities in cerebral palsy prevalence in the United Kingdom: a register based study. Pediatric and Perinatal Epidemiology 2010: 24; 149–155.

Dowding V, Barry C. Cerebral palsy: social class difference in prevalence in relation to severity of disability. Journal of Epidemiology and Community Health 1990: 44; 191–195.

Elder GC, Kirk J, Stewart G, Cook, Weir D, Marshall A, Leahey L. Contributing factors to muscle weakness in children with cerebral palsy. Dev. Med. Child Neurol. 2003; 45: 542-550.

Electrode positions. http://www.wg11.sc29.org/mpeg-v/wp-content/uploads/2012/09/emg1.png. Date accessed: 30/05/2013. *Sourced* from Neumann's Kinesiology of the musculoskeletal system, 2002.

Ema R, Wakahara T, Mogi Y, Miyamoto N, Komatsu T, Kanehisa H, Kawakami Y. In *vivo* measurement of human rectus femoris architecture by ultrasonography: validity and applicability. J. Clin. Physiol. Funct. Imaging. 2013; 33: 267-273.

Eston RG, Rowlands AV, Ingledew DG: Validity of heart rate podometry and accelerometry for predicting the energy cost of children's activities. J. Appl. Physiol. 1998; 84: 362–371.

External oblique muscle.
http://www.google.co.za/images?imgurl=filesexternalobliquesjpg&imgrefurl=http://www.myweightlifting.com/obliquemuscles. Date accessed: 30/05/2013.

Farris DJ, Sawicki GS. Human medial gastrocnemius force-velocity behaviour shifts with locomotion, speed and gait. Physiol. 2012; 109 (3): 977-982.

Fellows SJ, Kaus C, Thilmann AF. Voluntary movement at the elbow in spastic hemiparesis. Ann. Neurol. 1994; 36: 397-407.

Ferreira PH, Ferreira ML, Hodges PW. Changes in recruitment of abdominal muscles in people with low back pain: ultrasound measurement of muscle activity. Spine 2004; 29: 2560–2566.

Forkey JN, Quinlan ME, Shaw MA, Corrie JET, Goldman YE. Three-dimensional structural dynamics of myosin V by single-molecule fluorescence polarisation. Nature. 2003; 422: 399-404.

Fosang A, Baker R. A method for comparing manual muscle strength measurements with joint moments during walking. Gait & Posture. 2006; 24 (4): 406-411.

Frigo C, Crenna P. Multichannel sEMG in clinical gait analysis: a review and state-of-art. Clin. Biomech (Bristol, Avon) 2009; 24 (3): 236–245.

Fry NR, Childs CR, Eve LC, Gough M, Robinson RO, Shortland AP. Accurate measurement of muscle belly length in the motion analysis laboratory: potential for the assessment of contracture. Gait Posture 2003; 17: 119–24.

Fry NR, Gough M, Shortland AP: Three-dimensional realisation of muscle morphology and architecture using ultrasound. Gait & Posture, 2004, 20: 177–182.

Fukunaga T, Roy RR, Shellock FG, Hodgson JA, Edgerton VR. Specific tension of the human plantar flexors and dorsiflexors. J. Appl. Physiol. 1996; 80: 158–165.

Fukunaga T, Ichinose Y, Ito M, Kawakami Y, Fukashiro S. Determination of fascicle length and pennation angle in a contracting human muscle in vivo. J. Appl. Physiol. 1997; 82 (1): 354–358.

Fukunaga T, Kubo K, Kawakami Y, Fukushiro S, Kanehisa H, Maganari CN. In vivo behaviour of human muscle tendon during walking. Proc. Biol. Sci. 2001; 268: 229-233.

Fukunaga T, Kawakami Y, Kubo K, Kanehisa H. Muscle and tendon interaction during movements. Exercise & Sports Science Reviews. 2002;30:106–110.

Gage JR. The treatment of gait problems in cerebral palsy. 2004; 103-110: 3rd ed.. Mac Keith Press,,London.

Gangata H. Parameters related to equinus ankle in ambulatory children with cerebral palsy: an investigation of the differences between children with the diplegic and hemiplegic subtypes. A Master of Science Dissertation (2008). University of Cape Town.

Gans C, Gaunt AS. Muscle architecture in relation to function. J. Biomechanics. 1991; 24 (suppl): 53-65.

Gao F, Zhao H, Gaebler-Spira D, Zhang LQ. In vivo evaluations of morphologic changes of gastrocnemius muscle fascicle and archilles tendon in children with cerebral palsy. Am. J. Phys. Med. Rehabil. 2011; 90: 364–371.

Getchell N, McMenamin S, Whitall J. Dual motor task coordination in children with and without learning disabilities. Adapted Physical Activity Quarterly. 2005; 22: 21-38.

Gyi DE, Sims Re, Porter JM, Marshall R, Case K. Representing older and disabled people in virtual user trials: data collections methods. J. Applied Ergonomics, 2004; 35(5): 443-451.

Goh HT, Thompson M, Huang WB, Schafer S. Relationship among measures of knee musculoskeletal impairments, gross motor function and walking efficiency in children with cerebral palsy. Pediatr. Phys. Ther. 2006; 18: 253–261.

Gormley ME. Treatment of neuromuscular and musculoskeletal problems in cerebral palsy. Pediatr. Rehabil. 2001; 4; 5–16.

Gorter JW, Rosenbaum PL, Hanna SE, Palisano RJ, Barlett DJ, Russell DJ, Walter SD, Raina P, Galuppi BE, Wood E. Limb distribution, motor impairment and functional classification of cerebral palsy. Dev. Med. Child Neurol. 2004; 46: 461-467.

Gough M, Shortland AP. Could muscle deformity in children with spastic cerebral palsy be related to an impairment of muscle growth and altered adaptation? Dev. Med. Child Neurol. Review. 2012; D0I:10.1111/j.1469-8749.2012.04229.x.

Graham HK, Fixsen JA. Lengthening of the calcaneal tendon in spastic hemiplegia by the white slide technique: a long-term review. J. Bone Joint Surg. Br. 1988; 70B: 472 - 475.

Gross motor function measure (GMFM) study tool (Appendix XI). www.fhs.mcmaster.ca/canchild. Date accessed: 30/01/2012.

Hagberg B, Hagberg G, Beckung E, Uvebrant P. Changin panorama of cerebral palsy in Sweden. VIII. Prevalence and origin in the birth type year period 1991-94. Acta Paediatr. 2001; 90: 271-277.

Hedrick W. Ultrasound Physics and Instrumentation. 2004; 22-38: 4th ed. Mosby Publ. New York.

Heimdal A, Stoylen A, Torp H, Skaerpe T. Real-time strain rate imaging of the left ventricle by ultrasound. J. Am. Soc. Echocardiogr. 1998; 11: 1013-1019.

Hensleigh PA, Fainstat T, Spencer R. Perinatal events and cerebral palsy. Am. J. Obstet. Gynecol. 1986; 154:978-981. Abstract.

Hermens HJ, Freriks B, Disselhurst-Klug C, Rau G. Development of recommendations for sEMG. Sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 2000; 10 (5): 361–374.

Higgins JPT, Green S (eds). Cochrane handbook for systematic reviews for interventions. 4.2.6. The Cochrane Library 2006 (4). John Wiley & Sons Ltd: Chischester.

Himmelmann K, Beckung E, Hagberg G, Uvebrant P. Bilateral spastic cerebral palsy: prevalence through four decades, motor function and growth. European Journal of Pediatric Neurology 2007; 11: 215–222.

Hip bone picture. http://fascstaff.gpc.edu/-jaliff/appendsk.htm. Date accessed: 30/05/2013.

Hjern A, Thorngren-Jerneck K. Perinatal complications and socio-economic differences in cerebral palsy in Sweden - a national cohort study. BMC Pediatrics 2008; 8: 49 [doi 10.1186/1471–2431-8-49].

Hlustik P, Solodkin A, Noll DC, Small SL. Cortical plasticity during three-week motor skill learning. J. Clin. Neurophysiol. 2004; 21 (3): 180–191.

Hodges PW. Is there a role for transversus abdominis in lumbo-pelvic stability? Manual Therapy 1999; 4 (2): 74–86.

Hodges PW. Ultrasound imaging in rehabilitation: just a fad? J.Orthop.Sports Phys.Ther. 2005; 35: 333-337.

Hodges PW, Richardson CA. Inefficient muscular stabilisation of lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine 1996; 21: 2640–2650.

Hodges PW, Richardson CA. Delayed postural contraction of transversus abdominis associated with movement of lower limb in people with low back pain. J. Spinal Disord. 1998; 11(1): 46-56.

Hodges P, Richardson CA. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speed. Archives of Physical Medicine and Rehabilitation. 1999; 80: 1005–1012.

Hodges PW, Pengel LHM, Herbert RD, Gandevia SC. Measurement of muscle contraction with ultrasound imaging. Muscle Nerve. 2003; 27: 682-692.

Hodges PW, Eriksson, AE, Shierley D, Gandevia SC. Intra-abdominal pressure increases stiffness of the lumbar spine. Journal of Biomechanics. 2005; 38 (9): 1873-1880.

Hodges PW. Pain and motor control: From the laboratory to rehabilitation. Journal of Electromyography and Kinesiology 2011; 21: 220–228.

Holzbaur KR, Murray WM, Gold GE, Delp SL. Upper limb muscle volumes in adult subjects. J Biomech 2007; 40: 742–9.

Huijing PA, Woittiez RD. The effect of architecture on skeletal muscle performance: a simple planimetric model. Neth. J. Zool. 1984; 34: 21-32.

Hurvitz EA, Green LB, Hornyak JE, Khuran SR, Koch LG. Body mass index measures in children with cerebral palsy related to gross motor function classification: A Clinic-Based study. Am. J. Phys. Med. Rehabil. 2007; 12: 1487-1496.

Hussain AW, Onambele GL, Williams AG, Morse CI. Muscle size, activation and coactivation in adults with cerebral palsy. Muscle & Nerve 2013 (1) [doi 10.1002/mus.23866].

Ichinose Y, Kawakami Y, Fukunaga T. In *vivo* measurement of fascicle arrangement in human vastus lateralis using ultrasound. In XVth Congress of the Int. Soc. Biomech. 1995; 421-413. Ed. Hakkinen K, Keskine KL, Komi PV, Mero A. Gummerus, Jyvaskyla, Finland.

Ijzerman MJ, Baardman G, van't Hof MA, Boom HK, Hermens HJ, Veltink PH: Validity and reproducibility of crunch force and heart rate measurements to assess energy expenditure of paraplegic gait. Arch. Phys. Med. Rehabil. 1999; 80: 1017–1023.

Ijzerman M, Nene AV. Feasibility of the physiological cost index as an outcome measure for the assessment of energy expenditure during walking. Arch. Phys. Med. & Rehab. 2002; 83 (12): 1777-1782.

Ikeda AJ, Abel MF, Granata KP, Damiano DL. Quantification of cocontraction in spastic cerebral palsy. Electromyogrr. Clinical Neurophysiol. 1998; 38: 497–504.

Infantolino BW, Challis JH. Architectural properties of the first dorsal interosseus muscle. J. Anat. 2010; 216: 463-469.

Internal oblique picture. www.teachpe.com/images/muscle/internal_obliquezoo. Date accessed: 30/05/2013.

Iwanuma S, Akagi R, Kurihara T, Ikegawa S, Kanehisa H, Fukunaga T, Kawakami Y. Longitudinal and transverse deformation of human Achilles tendon induced by isometric plantar flexion at different intensities. J. Appl. Physiol. 2011; 110: 1615-1621.

Jones C, Allen T, Talbot J, Morgan DL, Proske U. Changes in mechanical properties of human and amphibian muscle after eccentric exercise. Eur J. Appl. Physiol 1997; 76: 21–31.

Kasiulevicius V, Sapoka V, Filipaviciute R. Sample size calculation in epidemiological studies. Gerotologija. 2006; 7 (4): 225-231.

Kathuria S, Arora S, Ramesh V. Sjorgren-Larsson syndrome: importance of early diagnosis and aggressive physiotherapy. Dermatol. Online J. 2012; 18 (9): 11-20.

Kawakami Y, Abe T, Fukunaga T. Muscle fibre pennation are greater in hypertrophied than normal muscle. J. Appl. Physiol. 1993; 74: 270–2744.

Kawakami Y, Abe T, Kumo S, Fukunaga T. Training-induced changes in muscle architecture and specific tension. Eur. J. Appl. Physiol. 1995; 72: 37–43.

Kawakami Y, Muraoka T, Ito S, Kanehisa H, Fukunaga T. In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. Journal of Physiology. 2002; 540: 635–646.

Kawakami Y, Abe T, Kanehisa H, Fukunaga T. Human skeletal muscle size and architecture: variability and interdependence. Am. J. Hum. Biol. 2006; 18: 845-858.

Khamis S, Yizhar Z. Effect of feet hyperpronation on pelvic alignment in standing position. Gait & Posture 2007; 25: 127–134.

Klimstra M, Dowling J, Durkin JL, MacDonald M. The effect of ultrasound probe on muscle architecture measurement. J. Electromyogr. Kinesiology 2007; 17: 504-514.

Ko HI, Kim HJ, Lee BH. Relationsips between lower limb muscle architecture and activities and participation of children with cerebral palsy. Journal of Exercise Rehabilitation 2013; 9(3): 368–374.

Koes BW, Bouter LM, Beckerman H, van der Heijden GJ, Knipschild PG. Physiotherapy exercises and back pain: a blind review. British Medical Journal 1991; 302: 1572-1576.

Krageloh-Mann I, Hagberg G, Meisner C, Schelp B, Micaelis R. Bilateral spastic cerebral palsy - a comparative study between western Sweden I: Clinical patterns and disabilities. Dev. Med. Child Neurol. 1993; 35: 1037-1047.

Kremkau FW. Diagnostic ultrasound: principles, instruments and exercises. 2002: 67-79: 6th ed. Saunders Publ. Philadelphia, PA.

Lampe R, Grassl S, Mitternacht J, Gerdesmeyer L, Gradinger R. MRT-measurement of muscle volumes of lower extremes of youth spastic hemiplegia caused by cerebral palsy. Brain Dev. 2006; 28: 500–506.

Lauer RT, Johnston TE, Smith BT, Lee SC. Lower extremity muscle activity during cycling in adolescents with and without cerebral palsy. Clin. Biomech. (Bristol, Avon) 2008; 23 (4): 442–449.

Lauer RT, Stachouse CA, Shewokis PA, Smith BT, Tucker CA, McCarthy J. A time-frequency based electromyographic analysis technique for use in cerebral palsy. Gait Posture 2007b; 26 (3): 420–427.

Lauer RT, Smith BT, Shewokis PA, McCarthy J, Tucker CA. Time-frequency changes in electromyographic signals after hamstring lengthening surgery in children in cerebral palsy. J. Biomech. 2007a; 40 (12): 2738–2743.

Legerlotz K, Smith HK, Hing WA. Variation and reliability of ultrasonographic quantification of the architecture of medial gastrocnemius muscle in young children. Clin Physiol. Funct. Imaging. 2010; 30: 198–205.

Lichtwark GA, Wilson AM. Is Achilles tendon compliance optimised for maximum muscle efficiency during locomotion? J. Biomech. 2007; 40: 1768–1775.

Lichtwark GA, Bougolias K, Wilson AM. Muscle fascicle and series elastic element length changes along the length of human gastrocnemius during walking and running. J. Biomech. 2007; 40: 157-164.

Lieber RL, Friden J. Functional and clinical significance of skeletal muscle architecture. Muscle Nerve 2000; 23: 1647–1666.

Lieber RL, Steinman S, Barash IA, Chambers H. Structural and functional changes in spastic skeletal muscle. Muscle Nerve 2004; 29: 615–627.

Longmuir PE, Bar-Or O. Factors influencing the physical activity levels of youths with physical and sensory disabilities. Adapt. Phys. Activ. Q. 2000; 17: 40–53.

Maganaris CN, Paul JP. Tensile properties of the invivo human gastrocnemius tendon. Journal of Biomechanics. 2002; 35: 1639–1646.

Maganaris CN, Baltzopoulos V, Sargeant AJ. In vivo measurement of triceps surae complex architecture in man: implications for muscle function. Journal of Physiology. 1998; 512 (Pt 2): 603-614.

Malaiya R, McNee AE, Fry NR, Eve LC, Gough M, Shortland AP. The morphology of the medial gastrocnemius in typically developing children and children with spastic hemiplegic cerebral palsy. J Electromyogr Kinesiol 2007; 17: 657–663.

Marshll P, Murphy B. The validity and reliability of surface EMG to assess the neuromuscular response of abdominal muscles to rapid limb movement. Journal of Electromyography & Kinesiology 2003; 13: 477–489.

McCrory MA, Mole PA, Nommsen –Rivers LA, Dewey KG. Between-day and within-day variability in the relation between heart rate and oxygen consumption effect on the estimation of energy expenditure by heart rate monitoring. Am. J. Clin. Nutr. 1997; 66: 18–25.

McGill SM. A revised anatomical model of the abdominal musculature for torso flexion efforts. J. Biomechanics 1996; 29: 973-977.

McMeeken JM, Beith ID, Newham DJ, Milligan P, Critchley DJ. The relationship between EMG and change in thickness of transversus abdominis. Clinical Biomech. 2004; 19: 337-342.

Misuri G, Colagrande S, Gorini M, Iandelli I, Mancini M, Duranti R, Scano G: In vivo ultrasound assessment of respiratory function of abdominal muscles in normal subjects. Eur. Respir. J. 1997; 10: 2861-2867.

Mitsiopoulos N, Baumgartner RN, Heymsfield SB, Lyons W, Gallagher D, Ross R. Cadaver validation of skeletal muscle measurement by magnetic resonance imaging and computerized tomography. J. Appl. Physiol. 1998; 85: 115–122.

Mohagheghi AA, Khan T, Meadows TH, Giannikas K, Baltzopoulos V, Maganaris CN. Differences in gastrocnemius muscle architecture between paratic and non-paretic legs in children with hemiplegic cerebral palsy. J. Clinical Biomechanics 2007; 22: 721–724.

Moore KL, Dalley AF, Agur AMR. Clinically Oriented Anatomy. 2005; 196-207: 5th ed. Lippincott Williams & Wilkins Publ. Philadelphia.

Moreau NG, Teefey SA, Damiano DL: In vivo muscle architecture and size of rectus femoris and vastus lateralis in children and adolescents with cerebral palsy. Dev. Med. & Child Neurology, 2009; 51: 800–806.

Moreau NG, Teefey SA, Damiano DL. Muscle architecture predicts maximum strength and is related to activity levels in cerebral palsy. Phys. Ther. 2010; 90: 1619-1630.

Moreau NG, Holthaus K, Marlow N. Differential adaptations of muscle architecture to high-velocity versus traditional strength training in cerebral palsy. Neurorehabil. & Neur. Repair. 2013; 24 (4): 325-334.

Morrel SD, Pearson MJ, Sauser D. Progressive bone and joint abnormalities of the spine and lower extremities in cerebral palsy. Radiographics 2002; 22: 257-268.

Moseley GL, Hodges PW. Are the changes in postural control associated with low back pain caused by pain interference? Clin. J. Pain. 2005; 21 (4): 323-329.

Moses KP, Banks JC, Nava PB, Peterson D. Atlas of Clinical Gross Anatomy. 2005;422-430 Elsevier Mosby Pub. Madrid.

Mossberg KA. Reliability of a timed walk test in persons with acquired brain injury. Am. J. Phys. Med. Med. Rehabil. 2003; 82: 385-390.

Muramatsu T, Muraoka T, Kawakami Y, Shibayama A, Fukunaga T: In vivo determination of fascicle curvature in contracting human skeletal muscles. J. Appl. Physiol. 2002; 92: 129–134.

Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Fukunaga T. In vivo mechanical properties of distal aponeuroses in human tibialis anterior muscle. J. Cells Tissues Organs. 2002b; 170: 162–169.

Murphy KP, Molnar GE, Lankasky K. Medical and functional status of adults with cerebral palsy. Dev. Med. Child Neurol. 1995; 37: 1075–1084.

Muscle attachments on the bony pelvis. http://www.musicstrong.com/anterior-pelvic-t. Date accessed: 30/05/2013.

Narici MV, Roi GS, Landoni L, Minetti AE, Cerretelli P. Changes in force, cross-sectional area and neural activation during strength training and detraining of human quadriceps. Eur. J. Appl. Physiol. 1989; 59: 310–319.

Narici MV, Binzoni T, Hiltbrand E, Fasel J, Terrier F, Ceretelli P. In vivo human gastrocnemius architecture with changing joint angle at rest and during guarded isometric contraction. J. Physiol. 1996; 496 (1): 287-297.

Nene AV: Physiological cost index of walking in able-bodied adolescents and adults. Clin.. Rehabil. 1993; 7: 319–326.

Nene AV, Jennings SV. Physiological cost index of paraplegic locomotion using the ORLAU parawalker. Paraplegia. 1992; 30: 246-252.

Nene AV, Evans GA, Parick JH: - Simultaneous multiple operations for spastic diplegia: Outcome and functional assessment of walking in 18 patients. J. Bone Joint Surg. Br. 1993; 75: 488-494.

Neunhauserer D, Zebedin M, Obermoser M, Moser G, Tauber M, Niebauer J, Resch H, Galler S. Human skeletal muscle transition between fast and slow fibre types. Pflugers Arch – Eur. J. Physiol. 2011; 461: 537–543.

Ng JK, Kippers V, Richardson CA. Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode positions. Electromyogra Clin Neurophysiol 1998; 38 (1): 51–58.

Nicholson JH, Morton RE, Attfield S, Rennie D. Assessment of upper limb function in children with cerebral palsy lycra garments. Dev. Med. Child Neurol. 2001; 43 (6): 384–391.

Nudo RJ. Adaptive plasticity in motor cortex: implications for rehabilitation after brain injury. J. Rehabil Med 2003; (Suppl. 41): 7–10.

Odding E, Roebroeck ME, Stam HJ. The epidemiology of cerebral palsy: incidence, impairments and risk factors. Disabil Rehabil. 2006; 28(4): 183-191. Abstract.

Ohata K, Haruta T, Kato T, Nakamura T. Relation between muscle thickness, spasticity, and muscle limitation in children and adolescents with cerebral palsy. Dev. Med. Child Neurol. 2008; 50: 152–156.

Ohata K, Tsuboyama,T, Ichihashi N, Minami S. Measurement of muscle thickness as quantitative muscle evaluation for adults with cerebral palsy. Phys. Ther. 2009; 86: 1231–1239.

Olney SJ. Quantitative evaluation of cocontraction of knee and ankle muscles in normal walking. In: Winter DA, Norman RW, Wells RP, Hayes KC, Patla AE, editors. Biomechanics IX-A. Champaign (IL): Human Kinetics; 1985; 431-435.

Palastanga N, Field D, Soames R. Anatomy and Movement. 2009; 466-473, 4th ed. Butterworth & Heinemann Publ. London.

Palisano R, Rosebaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. Dev. Med. Child Neurol. 1997; 39: 214-223.

Palisano RJ, Hanna, SE, Rosenbaum PL, Russell DJ, Walter SD, Wood EP, Raina PS Galuppi BE: Validation of a model of gross motor function for children with cerebral palsy. Physical Therapy 2000, 80: 974–985.

Panjabi MM. The stabilising system of the spine. Part II. Neutral zone and instability hypothesis. Journal of Spinal Disorders. 1992a; 5: 390–397.

Panjabi MM. The stabilising system of the spine part I. Function, dysfunction adaptation and enhancement J. Spinal Disorders. 1992b; 5: 383–389.

Pelvic tilt picture. http://www.i.imgur.com/mtFaw.jpg. Date accessed: 30/05/2013.

Peper E, Gibney KH. Muscle Biofeedback at the computer. J. Biofeedback Foundation of Europe. 2006; 4: 186-192.

Peschers UM, Gingelmaier A, Jundt K, Leib B, Dimpfl T. Evaluation of pelvic floor muscle strength using four different techniques. Int. Urogynecol. J. Pelvic Floor Dysfunct. 2001; 12: 27-30.

Poon DM, Hui-Chan CW. Hyperactive stretch reflexes, co-contraction, and muscle weakness in children with cerebral palsy. Dev. Med. Child Neurol. 2009; 51: 128–135.

Prosser LA, Lee SCK, Barbe MF, VanSant AF, Lauer RT. Trunk and hip muscle activity in early walkers with or without cerebral palsy – A frequency analysis. Journal of Electromyography and Kinesiology 2010; 20: 851–859.

Raja K, Joseph B, Benjamin S, Minocha V, Rana B. Physiological cost index in cerebral palsy: its role in evaluating the efficiency of ambulation. J. Pediatr. Orthop. Int. 2007; 27 (2): 130-139.

Reeves ND, Maganaris CN, Narici MV. Ultrasonographic assessment of human skeletal muscle size. Eur. J. Appl. Physiol. 2004; 91: 116–118.

Reiman MP. Trunk stabilization training: an evidence basis for the current state of affairs. J.Back.Musculoskelet.Rehabil. 2009; 22: 131-142.

Richardson CA, Snijders CJ, Hides JA, Damen L, Pas MS, Storm J. The Relation Between the Transversus Abdominis Muscles, Sacroiliac Joint Mechanics, and Low Back Pain. Spine 2002; 27: 399–405.

Rivilis I, Hay J, Cairney J, Kletrou P, Liu J, Faught BE. Physical activity and fitness in children with developmental coordination disorder: a systematic review. Research in Devt Disaabilities. 2011; 32: 894-910.

Roncesvalles MN, Woollacott MH, Jensen JL. Development of lower extremity kinetics for balance control in infants and young children. J. Motor Behav 2001; 33 (2): 180–192.

Rose J, Medeiros JM, Parker R: Energy cost index as an estimate of energy expenditure of cerebral palsied children during assisted ambulation. Dev. Med. Child Neurol. 1985; 27: 485–490.

Rose J, Gamble JG, Burgos A, Mederos J, Haskell WL. Energy expenditure index of walking for normal children and for children with cerebral palsy. Dev. Med. Child. Neurol.. 1990; 32: 333–340.

Rose J, McGill KC. Neuromuscular activation and motor unit firing characteristics in cerebral palsy. Dev. Med. Child Neurol. 2005; 47 (5): 329–336.

Rosenbaum PL, Walter SD, Hanna SE, Palisano RJ, Russell DJ, Raina P, Wood E, Bartlett DJ, Galuppi BE. Prognosis for gross motor function in cerebral palsy: creation of motor development curves. JAMA. 2002; 18 (288):11; 1357-1363.

Rosenbaum P, Paneth N, Leviton A, Goldstein M, Bax M, Damiano D, Dan B, Jacobson B. A report: the defition and classification of cerebral palsy April 2006. Dev. Med. Child Neurol. 2007; (suppl.); 109: 8-14.

Ross SA, Engsberg JR. Relationship between spasticity, strength, gait and the GMFM-66 in persons with spastic diplegia cerebral cerebral palsy. Arch. Phys. Med. Rehabil. 2007; 88 (9): 1114–1120.

Russell DJ, Rosenbaum PL, Cadman DT, Gowland C, Hard S, Jarvis S. The gross motor function measure: a means to evaluate the effects of physical therapy. Dev. Med. Child Neurol. 1989; 31: 341-352.

Russell DJ, Avery LM, Rosenbaum PL, Raina PS, Walter SD, Palisano RJ. Improved scaling of gross motor function measure for children with cerebral palsy: evidence of reliability and validity. Phys. Ther. 2000; 80: 873–885.

Rutherford OM, Jones DA. Measurement of fibre pennation using ultrasound in human quadriceps in vivo. Eur. J. Appl. Physiol. Occup. Physiol. 1992; 65: 433–437.

Scholten RR, Pillen S, Verrips A, Zwarts MJ. Quantitative ultrasonography of skeletal muscles in children: normal values. Muscle Nerve 2003: 27: 693–698.

Sella GE, Finn RE. Myofacial Pain Syndrome: Manual Trigger Point & sEMG Biofeedback Therapy Methods. 2001:14-36: Int. ed. GENMED Publishing Inc, Martins Ferry, OH.

Shortland AP, Harris CA, Gough M, Robinson RO. Architecture of the medial gastrocnemius in children with spastic diplegia. Dev Med. Child Neurol. 2002; 44: 158–163.

Siminoski K, Warshawski RS, Jen H, Lee K. The accuracy of historical height loss for the detection of vertebral fracture in postmenopausal women. Osteoporos. Int. 2006; 17: 290-296. DOI 10. 1007/s00198-005-2017-y.

Sloan JP. Emergency Physician directed ultrasound. Ultrasound Magazine, 2004; 18-44.

Smith LR, Lee KS, Ward SR, Chambers HG, Lieber RL. Hamstring contractures in children with spastic cerebral palsy result from a stiffer extracellular matrix and increased in *vivo* sarcomere length. J. Physiol. 2011; 589 (10): 2625-2639.

Snijders CJ, Vleeming A, Stoekart R, Mens JMA, Kleinrensink GJ. Biomechanical modelling of the sacroiliac stability in different postures. Spine: State of the Art Reviews. 1995; 9: 419–432.

Stackhouse SK, Binder-Macleod SA, Lee SC: Voluntary muscle activation, contractile properties, and fatigability in children with and without cerebral palsy: Muscle & Nerve 2005; 31: 594–601.

Standring S.(editor-in-chief). In Gray's Anatomy: The anatomical basis of clinical practice, 2005. 39th ed.:1102 – 1103; Elsevier Publishers; Edinburgh, London. New York.

Stanley RB. The zygomatic arch as a guide to reconstruction of comminuted malar fractures. Arch Otolaryngol. Head & Neck Surgery, 1989; 115 (12): 1459–1462.

Statistica version 11 software. http://www.stat.com. Date accessed: 30/09/2012

Stephenson GM. Hybrid skeletal muscle fibres: a rare or common phenomenon? Clin. Exp. Pharmacol. Physiol. 2001; 28 (8): 692–702.

Stoylen A, Heimdal A, Bjornstad K, Wiseth R, Vik-Mo H, Torp H, Angelsen B, Skaerpe T. Strain rate imaging by ultrasonography in the diagnosis of coronary artery disease. J.Am. Soc. Echocardiogr. 2000; 13 (12): 1053–1064.

Sundrum R, Logan S, Wallace A, Spencer N. Cerebral palsy and socio-economic status: a retrospective cohort study. Archives of Disease in Childhood 2005: 90; 15–18.

Suzuki H, Conwit RA, Stashuk D, Santarsiero L, Metter EJ. Relationships between surface-detected EMG signals and motor unit activation. Med. & Sci. in Sports & Exer. 2002; 1509-1517.

Szoab T. Diagnostic Ultrasound Imaging: Inside Out. 2004; 46-70: Int'l. ed. Academic Press, London.

Ten-Berge SR, Halbertsma JPK, Maathuis PGM, Verheij NP, Dijkstra PU, Maathius KGB. Reliability of popliteal angle measurement: a study in cerebral palsy patients and healthy controls. J. Pediatr. Orthop. 2007; 27 (6): 648-652.

Teyhen DS, Rieger JL, Westrick RB, Miller AC, Molloy JM, Childs JD. Changes in deep abdominal muscle thickness during common trunk-strengthening exercises using ultrasound imaging. Journal of Orthopaedic & Sports Physical Therapy. 2008; 38: (10): 596-605.

Thomas SS, Moore C, Kelp-Lenane J, Norris C. Simulated gait patterns: the resulting effects on gait parameters, dynamic electromyography, joint moments and physiological cost index. Gait & Posture 1996; 4: 100–107.

Tobias PV, Arnold M, Allan JC. Man's anatomy: a study in dissection. 1988; 119-139:Student ed. Witwatersrand Univ. Press, Johannesburg.

Torloni MR, Vedmedovska N, Merialdi M, Betran AP, Allen T, Gonzalez R, Platt LD. Safety of ultrasonography in pregnancy: WHO systematic review of the literature and meta-analysis. Ultrasound Obstet. Gynecol. 2009; 33: 599–608.

Transversus abdominis picture. http://www.teachpe.com/images/google.co.za/images. Date accessed: 30/05/2013. *Sourced* from Anatomy of the human body, by Henry Gray. 20th ed.

Tsao H, Hodges PW. Immediate changes in feedforward postural adjustments following voluntary motor training. Experimental Brain Research 2007; 4: 537–546.

Tucker KJ, Hodges PW. Changes in motor unit recruitment strategy during pain alters force direction. Eur. J. Pain. 2010; 14: 932-938.

Unger M: The role of the abdominal Muscles in pelvic positioning and lower limb function in children with spastic type cerebral palsy. A PhD Dissertation, 2011; University of Cape Town.

Unger M, Faure M, Frieg A. Strength training in adolescent learners with cerebral palsy: a randomized controlled trial. Clin.Rehabil. 2006; 20:469-477.

Urquhart DM, Hodges P, Story I. Postural activity of the abdominal muscles between regions of these muscles and between body positions. Gait Posture. 2005; 22: 295-301.

Urquhart DM, Hodges PW, Allen TJ, Story IH. Abdominal muscle recruitment during range of voluntary exercises. Manual Ther. 2005; 10: 144-153.

van Dieen JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of lumbar spine. Spine 2003a; 28: 834–841.

van Dieen JH, Kingma I, van der Bug JCE. Evidence for a role of antagonistic cocontraction in controlling trunk stiffness during lifting. Journal of Biomechanics. 2003b; 36: 1829–1836.

van Gestel L, Wambacq H, Aertebeliesn E, Meyns P, Bruyninckx H, Bar-On L, Molenaers G, De Cock P, Desloovere K. To what extent is mean EMG frequency during gait a reflection of functional muscle strength in children with cerebral palsy? Research in Developmental Disabilities. 2012; 33: 916-923.

van Toorn R, Laughto B, van Zyl N. Aetiology of cerebral palsy in children presenting at Tygerberg Hospital. South African J, Child Health. 2007; 1 (2): 74-77.

Vasseljen O, Dahl HH, Mork PJ, Torp HG. Muscle activity onset in lumbar multifidus muscle recorded simultaneously by ultrasound imaging and intramuscular electromyography. Clinical Biomechanics. 2006; 21: 905-913.

Vasseljen O, Fladmark AM, Westad C, Torp HG: Onset in abdominal muscles recorded simultaneously by ultrasound imaging and intramuscular electromyography. J. Electromyography & Kinesiology 2009; 19: e19 – e23.

Verschuren O, Ketelaar M, Takken T, van Brussel M, Helders P, Gorter JW. Reliabity of hand-held dynamometry and functional strength tests for the lower extremity in children with cerebral palsy. Disabil. Rehabil. 2008:30; 1350 – 1366.

Viaz G, Roussouly P, Berthonnaud E, Dimnet J. Sagittal morphology and equilibrium of pelvis and spine. Eur. Spine J. 2002; 11: 80 – 87. DOI. 10.10007/ s005860000224.

Walker FO, Cartwright MS, Wiesler ER, Caress J. Ultrasound of nerve and muscle. Clin. Neurophysiol. 2004; 115: 495-507.

Wakahara T, Takeshita K, Kato E, Miyatani M, Tanaka NI, Kanehisa H, Kawakami Y, Fukunaga T. Variability of limb muscle size in young men. Am. J.Hum. Biol. 2010; 22: 55-59.

Wakahara T, Miyamoto N, Sgissaki N, Murata K, Kanehisa H, Kawakami Y, Fukunaga T, Yanai T. Association between regional differences in muscle activation in one session of resistance exercise and muscle hypertrophy after resistance training. Eur. J. Appl. Physiol. 2012; 112: 1569-1576.

Wakeling J, Delaney R, Delaney R, Dudkiewiecz I. A method for quantifying dynamic muscle dysfuntion in children and young adults with cerebral palsy. Gait Posture 2007; 25 (4): 580–589.

Westborn L, Hagglund G, Nordmark E. Cerebral palsy in total population of 4 – 11 year olds in southern Sweden: Prevalence and distribution according to different systems. BMC, 2007; Pediatr 5 (7): 41.

Wickiewicz TL, Roy RR, Powell PL, Edgerton VR. Muscle architecture of human lower limb. Clinical Orthopaedics & Related Research. 1983; 275-283.

Wiley ME, Damiano DL: Lower- extremity strength profiles in spastic cerebral palsy. Devt. Med. & Child Neurology. 1998; 40: 100–107.

Winchester P, McColl R, Query R, Foreman N, Mosby J, Tansey K, Williamson J. Changes in supraspinal activation patterns following robotic locomotor therapy in motor-incomplete spinal cord injury. Neurorehab. Neural Rep. Re. 2005; 19 (4): 313–324.

Winter DA. Biomechanics and motor control of human movement. 1990; 114-117: 2nd ed. JohnWiley Publ. New York.

Winters TF, Gage JR, Hicks R. Gait patterns in spastic hemiplegia and young adults. J Bone Joint Surg Am 1987; 69(3): 437-441.

Woittiez RD, Huijing PA, Boom HB, Rozendal RH. A three-dimensional muscle model: a quantified relation between form and function of skeletal muscles. Journal of Morphology. 1984; 182: 92–113.

Wood EP, Rosenbaum PL. The gross motor function classification system for cerebral palsy: a study of reliability and stability over time. Dev. Med. Child Neurol. 2000; 42: 292-296.

Woollacott M, Shumway-Cook A, Hutchinson S, Ciol M, Price R, Kartin D. Effect of balance training on muscle activity used in recovery of stability in children with cerebral palsy: a pilot study. Dev. Med. Child Neurol. 2005; 47: 455-61.

World Health Organisation. International classification of functioning disability and health, ICF. 2001. Geneva, WHO.

Wu J, Looper J, Ulrich BD, Ulrich DA, Angulo-Barroso RM. Exploring effects of different treadmill interventions in walking onset and gait patterns in infants with Down Syndrome. Dev. Med. Child Neurol. 2007; 49 (11): 839–945.

Young A, Stokes M, Crowe M. Size and strength of the quadriceps muscles of old and young women. Eur. J. Clin. Invest. 1984; 14: 282–287.

Young S. New research centre to study basis of mobility disorders using powerful 3-D simulation patients' movements. http: //mednews.stanford.edu/Jan 2011.

Yue G, Alexander AL, Laidlaw DH, Gmitro AF, Unger EC, Enoka RM. Sensitivity of muscle protein spin-spin relaxation time as an index of muscle activation. J.Appl.Physiol. 1994; 77: 84-92.

Zajac EF. Muscle and tendon: Properties, models, scaling and application to biomechanics and motor control. Critical Reviews in Biomed. Eng.1989; 17: 359-411.

Zwaan E, Becher JG, Harlaar J. Synergy of EMG patterns in gait as an objective measure of muscle selectivity in children with spastic cerebral palsy. Gait & Posture. 2012; 35: 111-115.

Chapter 8 Appendices

Appendix A. Ethical considerations

Appendix A 1: Ethical approval by the Human Research Ethics Committee (UCT)

UNIVERSITY OF CAPE TOWN

Health Sciences Faculty
Human Research Ethics Committee
Room E52-24 Groote Schuur Hospital Old Main Building
Observatory 7925
Telephone [021] 406 6338 • Facsimile [021] 406 6411
e-mail: shuretta.thomas@uct.ac.za

17 November 2011

HREC REF: 490/2011

Mr S Adjenti
c/o Prof G Louw
Human Biology

Dear Mr Adjenti

PROJECT TITLE: AN INVESTIGATION INTO THE ULTRA STRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY.

Thank you for addressing the queries raised by the Faculty of Health Sciences Human Research Ethics Committee.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

Approval is granted for one year till the 28 November 2012.

Please submit a progress form, using the standardised Annual Report Form (FHS016), if the study continues beyond the approval period. Please submit a Standard Closure form (FHS010) if the study is completed within the approval period.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the HREC. REF in all your correspondence.

Yours sincerely

PROFESSOR M BLOCKMAN
CHAIRPERSON, HSF HUMAN ETHICS
Federal Wide Assurance Number: FWA00001637.
Institutional Review Board (IRB) number: IRB00001938

s.thomas

Appendix A 2: Approval by the Human Research Ethics Committee for ammendment of protocol

UNIVERSITY OF CAPE TOWN

Faculty of Health Sciences
Human Research Ethics Committee
Room E52-24 Groote Schuur Hospital Old Main Building
Observatory 7925
Telephone [021] 406 6626 • **Facsimile** [021] 406 6411
e-mail: shuretta.thomas@uct.ac.za

6 December 2012

HREC REF: 490/2011

Mr S Adjenti
c/o Prof G Louw
Human Biology
Room 4.06
Anatomy Building

Dear Mr Adjenti

PROJECT TITLE: AN INVESTIGATION INTO THE ULTRA STRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY

Thank you for submitting your amendment to the Faculty of Health Sciences Human Research Ethics Committee.

The HREC have **noted and approved** the minor amendment for the above-mentioned study including the following:

- Recruiting of a new group
- Replacement of Gross motor Function Measure (GMFM) and Physiological cost Index (PCI) measurements
- Child Assent Form (for child with developmental co-ordination disorders)
- Parent / Guardian Assent Form

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the HREC REF in all your correspondence.

Yours sincerely,

PROFESSOR MARC BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS

S Thomas

Appendix A 3: Permission from the Department of Education

Western Cape Government
Education

Directorate: Research

Audrey.wyngaard2@pgwc.gov.za
tel: +27 021 467 9272
Fax: 0865902282
Private Bag x9114, Cape Town, 8000
wced.wcape.gov.za

REFERENCE: 2011202-0028
ENQUIRIES: Dr A T Wyngaard

Mr Saviour Adjenti
Faculty of Health Sciences
UCT
Rondebosch

Dear Mr Saviour Adjenti

RESEARCH PROPOSAL: AN INVESTIGATION INTO THE ULTRA STRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY (STCP)

Your application to conduct the above-mentioned research in schools in the Western Cape has been approved subject to the following conditions:

1. Principals, educators and learners are under no obligation to assist you in your investigation.
2. Principals, educators, learners and schools should not be identifiable in any way from the results of the investigation.
3. You make all the arrangements concerning your investigation.
4. Approval for projects should be conveyed to the District Director of the schools where the project will be conducted.
5. Educators' programmes are not to be interrupted.
6. The Study is to be conducted from **01 February 2013 till 30 August 2013**
7. No research can be conducted during the fourth term as schools are preparing and finalizing syllabi for examinations (October to December).
8. Should you wish to extend the period of your survey, please contact Dr A.T Wyngaard at the contact numbers above quoting the reference number?
9. A photocopy of this letter is submitted to the principal where the intended research is to be conducted.
10. Your research will be limited to the list of schools as forwarded to the Western Cape Education Department.
11. A brief summary of the content, findings and recommendations is provided to the Director: Research Services.
12. The Department receives a copy of the completed report/dissertation/thesis addressed to:

    The Director: Research Services
    Western Cape Education Department
    Private Bag X9114
    CAPE TOWN
    8000

We wish you success in your research.

Kind regards.
Signed: Dr Audrey T Wyngaard
for: **HEAD: EDUCATION**
DATE: 23 January 2013

WESTERN CAPE
Education Department
Provincial Government of the Western Cape

RES
EAR
CH

Audrey.Wyngaard2@pgwc.gov.za
tel: +27 021 476 9272
Fax: 0865902282
Private Bag x9114, Cape Town, 8000
wced.wcape.gov.za

REFERENCE: 20111202-0028
ENQUIRIES: Dr A T Wyngaard

Mr Saviour Adjenti
Faculty of Health Sciences
UCT
Rondebosch

Dear Mr Saviour Adjenti

RESEARCH PROPOSAL: AN INVESTIGATION INTO THE ULTRA STRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY (STCP)

Your application to conduct the above-mentioned research in schools in the Western Cape has been approved subject to the following conditions:

1. Principals, educators and learners are under no obligation to assist you in your investigation.
2. Principals, educators, learners and schools should not be identifiable in any way from the results of the investigation.
3. You make all the arrangements concerning your investigation.
4. Educators' programmes are not to be interrupted.
5. The Study is to be conducted from **01 February 2012 till 30 August 2012**
6. No research can be conducted during the fourth term as schools are preparing and finalizing syliabi for examinations (October to December).
7. Should you wish to extend the period of your survey, please contact Dr A.T Wyngaard at the contact numbers above quoting the reference number.
8. A photocopy of this letter is submitted to the principal where the intended research is to be conducted.
9. Your research will be limited to the list of schools as forwarded to the Western Cape Education Department.
10. A brief summary of the content, findings and recommendations is provided to the Director: Research Services.
11. The Department receives a copy of the completed report/dissertation/thesis addressed to:

    The Director: Research Services
    Western Cape Education Department
    Private Bag X9114
    CAPE TOWN
    8000

We wish you success in your research.

Kind regards.
Signed: Audrey T Wyngaard
for: **HEAD: EDUCATION**
DATE: 02 December 2011

Appendix A 4: Ethical approval of annual progress report

UNIVERSITY OF CAPE TOWN

HUMAN RESEARCH ETHICS COMMITTEE
30 OCT 2012
30 NOV
FACULTY

FACULTY OF HEALTH SCIENCES
Human Research Ethics Committee

FHS016: Annual Progress Report / Renewal

HREC office use only (FWA00001637; IRB00001938)			
This serves as notification of annual approval, including any documentation described below.			
☑ Approved	Annual progress report Approved until/next renewal date		28.11.2013
☐ Not approved	See attached comments		
Signature Chairperson of the HREC		Date Signed	7/11/12

Principal Investigator to complete the following:

1. Protocol information

Date form submitted			
HREC REF Number	490/2011	Current Ethics Approval was granted until	28-11-12
Protocol title	AN INVESTIGATION INTO THE ULTRASTRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY.		
Protocol number (if applicable)			
Principal Investigator	Saviour ADJENTI		
Department / Office Internal Mail Address	DEPT. OF HUMAN BIOLOGY, ANATOMY BUILDING, ANZIO ROAD, OBSERVATORY, UCT.		

1.1 Does this protocol receive US Federal funding?	☐ Yes	☑ No
1.2 Has sponsorship of this study changed? If yes, please attach a revised summary of the budget.	☐ Yes	☑ No

2. List of documentation

(Note: Please complete the Closure form (FHS010) if the study is completed within the approval period)

Appendix A 5: Approval of closure of study from Human Research Ethics Committee

UNIVERSITY OF CAPE TOWN

FACULTY OF HEALTH SCIENCES
Human Research Ethics Committee

Form FHS010: Study Closure Report

HREC office use only (FWA00001637; IRB00001938)			
Noted and filed. This serves as acknowledgement that this study is closed.			
☑ Approved	Study closure report		
☐ Not Approved	Study closure report		
Chairperson of the HREC signature		Date	31/10/2013

1. Principal Investigator to complete the following:

Date	31 – 10 – 2013
HREC REF Number	490 / 2011
Protocol Title	AN INVESTIGATION INTO THE ULTRASTRUCTURE OF ABDOMINAL MUSCLE PARAMETERS AND THEIR EFFECT ON ANTERIOR PELVIC TILT IN CHILDREN AND ADOLESCENTS WITH SPASTIC TYPE CEREBRAL PALSY.
Protocol number (if applicable)	→ 490/2011
Principal Investigator	SAVIOUR ADJENTI
Department / Office Internal Mail Address	HUMAN BIOLOGY, Room 4.06, ANATOMY BUILDING

2. Please confirm (tick √)

This study is closed to enrollment	☑ Yes	☐ No
Participants have completed all research-related interventions	☑ Yes	☐ No
Participants have completed all research-related follow-up	☑ Yes	☐ No
Data analysis is complete	☑ Yes	☐ No
Your sponsored protocol is closed	☑ Yes	☐ No
If you answered 'no' to any of the above questions, you must keep your study open until all research activity is completed.		

3. What is the reason for closing the study? (tick √)

Research completed	✓	No time	
Terminated due to toxicity/adverse event		PI left UCT or affiliated sites	

Slow accrual		Insufficient funding	
Loss of interest		Research never began	
Other. Please specify:			

4. Please indicate how and for how long the data will be stored and protected

- Sonographs generated are to be stored for good. To form the reference materials for future research. Confidentiality is assured.

5. Please list or attach any papers, abstracts, presentations or other outputs generated from this study

- Writing up in a bid to compile findings into a PhD dissertation.

6. Signatures

Signature of PI:		Date	30-10-13
Signature of Supervisor (if PI is a student)		Date	30/10/2013

Appendix A 6: Sample letter of invitation to parents / guardians

Friends Day Centre

Special Care And Activity Centre For People With Severe & Profound Intellectual And Physical Disabilities

WO 3020027 / 006 - 245 - NPO / PBO: 130002579 Sect 18a:18/11/13/2579

PO BOX 229 7404 MAITLAND
CAPE TOWN SOUTH AFRICA
TEL: +27 21 511 5801
www.friendsdaycentre.org.za

10 May 2012

Dear Parents / Guardians

The Centre has been approached to be part of a ~~Masters~~ doctoral research study to investigate the abdominal (tummy) muscle function in children with Cerebral Palsy.

We would hereby like to request your permission for your child's participation in the above mentioned study. Attached are consent forms that need to be completed and returned as soon as possible.

If you have any concerns or questions, please feel free to contact the Centre / Physio department

Kind Regards

Liezl Müllenberg
Physio Dept

Appendix A 7: Translation of letter of invitation into Afrikaans

24 February 2012

Dear Parents,

A student asked us if he could do a research project at Paarl School. He needs learners for his project. His name is Saviour Adjenti, and he is a Phd. student in Human Biology at the University of Cape Town. We identified your child as a possible candidate for the study. It is totally voluntary and does not affect the therapy at school. The forms (that explains everything) are included. Please fill in both forms if you are willing to let your child participate in the study, and send back to school by Monday. If you do not want your child to be part of this study, please send the empty forms back to school.

Thank you

The physiotherapists

24 Februarie 2012

Geagte Ouers,

'n Student het ons genader t.o.v. 'n navorsingstudie wat hy graag by die skool wil doen. Hy benodig leerders vir sy studie. Sy naam is Saviour Adjenti, en hy is 'n Phd student in Menslike Biologie by die Universiteit van Kaapstad. Ons het u kind geidentifiseer as 'n moontlike kandidaat vir die studie. Dit is heeltemal vrywillig en onafhanklik van die terapie wat by die skool aangebied word. Ons stuur die vorms (waarin alles verduidelik word) saam huistoe. Indien dit u goedkeuring wegdra, vul asb.beide vorms in en stuur teen Maandag terug skooltoe. Indien u nie wil hê u kind moet deel wees van die studie nie,stuur asb.steeds die vorms terug na fisioterapie.

Baie dankie

Die fisioterapeute

Appendix A 8: Informed child assent / consent form for children with STCP

Name:..... Grade: .....

Child Assent Form (*for child with STCP*)

UNIVERSITY OF CAPE TOWN FACULTY OF HEALTH SCIENCES

PARTICIPANT INFORMATION LEAFLET AND ASSENT FORM

TITLE OF THE RESEARCH PROJECT:

An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy.

RESEARCHER'S NAME(S): Saviour Adjenti **(HREC REF 490 / 2011)**

ADDRESS: University of Cape Town

Faculty of Health Science

Dept of Human Biology

CONTACT NUMBER: 078 065 2713

What is RESEARCH?

Research is something we do to find new knowledge about the way things (and people) work. We use research projects or studies to help us find out more about disease or illness. Research also helps us to find better ways of helping, or treating children who are sick.

What is this research project all about?

This study wants to look at the 'inside' of your tummy muscle to see what is in them that is making them look stronger or weaker, so that we can know what is making them not to make you stand upright and walk properly.

For us to be able to do this study, we will measure how tall you are and how much you weigh. By putting a probe on your tummy muscles – called ultrasound (*the same machine your mommy had to see what you looked like before you were born!*) while you are lying down and when you are standing to see how thick or thin your tummy muscles are. This will also be done when moving your leg and head forward while lying down and also your arm forward. We will measure how much your tummy muscles work inside you with another machine in contact with the skin of your tummy muscles (electromyograph –EMG). You *may* also be asked to lift small weights, take a rest and repeat it for about 10 to 15mins to enable us judge how your tummy muscles are made. You *may* be asked to walk on a carpet for a small machine to measure how you walk. If you are above 12 years of age and also having anaesthetic treatment from your doctor during the study period, then you *may* be selected to provide a little bit of flesh from each of your four tummy muscles through a special needle which your doctor will put in them. This bit of flesh will later be put in a special machine and

then whatever is seen compared with those pictures that are seen in science books of your age mates, who can stand and walk properly. If it becomes necessary that you do this, then your doctor will do it any time s/he is treating you, if you are selected to do this test. Lastly you may be driven in my school's car with two other mates of yours and myself to the Medical School during your break time, where we will also take some photographs of your tummy and waist with some type of X-ray machine (called Lodox), while you lie on one side of your body to see how your waist looks like when you are upstanding. None of these tests will cause any pain, but if you are scared, you can just watch first when we do it on other friends of yours and you can also be allowed to do some practice first.

Why have I been invited to take part in this research project?

You have been invited to participate because you have spastic cerebral palsy and because you go to Eros school.

Who is doing the research?

I am Saviour Adjenti, I used to teach medical and physiotherapy students about the human body in Accra, Ghana. Now I have registered for a higher degree at the University of Cape Town. I am doing this study so that I can get my PhD degree and also come out with new findings that may help your therapist improve your treatment.

Can anything bad happen to me?

Nothing bad can happen and should you hurt yourself by accident, the nurse will help you and I will phone your parents to tell them about it.

Can anything good happen to me?

Hopefully, depending on what we find, your therapists may use that to help make your tummy muscles get stronger and that may help you walk better and stand and sit more upright. Balancing of your body may also get better.

Will anyone know I am in the study?

Only myself, my research assistant – she is also a physiotherapist - and my study supervisors at the university will know you are in the study. I will not use your name anywhere, so nobody will be able to know you took part. If you agree to it, I may want to use one of your photographs in an article to be published in a professional journal, but will not do so if you do not agree.

Who can I talk to about the study?

You can talk to me (078 065 2713). You can also talk to the Physiotherapists at the school. You can also talk to any of my supervisors (Prof Louw 021- 406 6302, Prof Jelsma 021-406 6595 & Dr Unger 021-938 9302).

What if I do not want to do this?

You can change your mind at any time. It will not affect your therapy at all.

Do you understand this research study and are you willing to take part in it?

YES / NO

Has the researcher answered all your questions?

YES / NO

Do you understand that you can withdraw from the study at any time?

YES/ NO

_____ _____

Signature of Child Date

Appendix A 9: Informed consent form for parents / guardians of children with STCP

Name of Child: ..... Grade: .....

Title of the project: An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy.

Principal investigator: Saviour Adjenti, MPhil Anatomy (HREC REF 490 / 2011)

Address: University of Cape Town, Faculty of Health Sciences, Department of Human Biology.

Parent / Guardian Assent Form (*for child with STCP*)

You and your child are being invited to take part in a research project. Please read the information in this letter, and feel free to ask the study staff about anything that is unclear to you. Participation is entirely voluntary, and your child's future medical treatment will not be negatively influenced if you decide not to take part. If you do agree to participate, you are free to withdraw from the study at any time without your child's future medical treatment being influenced whatsoever.

Approval of this study is given by the Ethics Committee for Human Research at The Faculty of Health Sciences, University of Cape Town, and will be conducted according to the South African Guidelines for Good Clinical Practice and the Medical Research Council (MRC) Ethical Guidelines for Research. Permission from the Headmaster of your child's school as well as the Department of Education has been obtained.

What is the study about?

This study is to investigate the fine structure of the abdominal muscles of children with spastic type of cerebral palsy, such as presented by your child, using ultrasound imaging, electromyography, some form of X-ray (Lodox) and physical activities. The aim is to gather as much information as possible on the fine structure of the abdominal muscles using non-invasive means and then compare these results with those from children with typical development in order to help therapists better understand the contribution of muscle strength or weakness in the tummy muscles to walking and balancing functions.

What do you need to do?

You may ask to be present during testing or attend any of the exercise sessions, however your assistance is not essential. Your child will be tested and take part in the exercise program during school hours in their therapy sessions. The tests include the following:

Your child's height and weight will be measured, and the thickness of your child's tummy muscles will be measured using ultrasound, which involves placing a probe on the skin on the side of the tummy muscles while your child is lying down motionless, while lying down and moving head forward, lying down and moving one leg up and also while he/ she is standing. sEMG with probes fixed to the skin of the tummy muscles will measure the activity of the tummy muscles of your child during these postures. In addition, your child would also be asked to do small weight lifting exercise (according to his or her abilities) for about 15mins. Your child and two other children with this condition, in company of the principal investigator *may* be transported to the Medical School's Anatomy Building in a university car by a professional driver working with the school, where photographs in the form of Lodox (X-ray) will be taken to show your child's posture but *not* his or her face. This trip will be undertaken during children's break or free times. Your child may also be asked to walk a short distance on a carpeted floor for a machine to measure how he/she walks. Additionally, should your child be above 12 years old and also undergoing anaesthetic treatment from his or her Anaesthetist/ Orthopaedic Surgeon during the study period, then he or she *may* be selected to provide a little bit of flesh from each of the four tummy muscles through a special needle. This bit of flesh will be put in a special machine and then whatever is seen compared with that of typically developing children as seen in textbooks. This exercise will be carried out by the child's orthopaedic surgeon/ anaesthetist, should the need arises. None of these tests will cause any pain, but should your child experience any anxiety or fear, (s)he can observe as well as have time to familiarize him/herself with all the tests.

Why have you been invited to take part?

Your child has been invited to take part as he/she fulfils all the criteria for inclusion into this study, i.e. he or she is between 6 and 18 years old and is part of this school which is chosen for the study.

Will you benefit from taking part?

As the study does not involve any form of treatment, your child will therefore not benefit directly, however knowledge gained from this study should enable therapists to better understand the role of the trunk (abdominal) muscles in children and therefore contribute to better decision-making regarding children with physical/motor problems. Neither you nor your child will be paid to take part in this study, nor will you incur any costs.

Are there any risks?

No known side effects or risks have been reported for the testing procedure that your child will undergo. No known allergic reactions to the gel, which serves as a contact medium for the head of the ultrasound machine, have ever been reported. Neither do the sEMG probe nor electrode placements except for a brief moment of a feeling of tingling sensation upon contact. The Lodox picture taking exercise is also safe and painless, should your child be chosen to take part in that too, so also is the short walk on the carpet, it does not involve any fatigue and at child's own pace.

Will my child remain anonymous?

None of your child's personal details will be made known to anyone other than the research staff, and will not be published in any form. The data of your child will be stored and presented anonymously. All images and video recordings will be destroyed after completion of the study.

What happens if I have any questions?

You are welcome to address any questions to **Saviour Adjenti on 078 065 2713** at any time. You are also welcome to contact the Committee for Human Research of the Faculty of Health Sciences, University of Cape Town on **(021) 406 6338** if you have any questions, or complaints that have not been answered by the study staff.

What happens afterwards?

If you wish, you will be sent the results of the study as soon as they become available which you will be able to discuss with the primary researcher (Saviour Adjenti).

About the researcher

Saviour Adjenti is a former Human Anatomy lecturer of the Ghana Medical School, Accra and now a registered PhD student in the Department of Human Biology, Faculty of Health Sciences, University of Cape Town. He has an M.Phil degree in Anatomy and is doing this research with supervisions from one anatomist and two physiotherapy professors, one of whom is a regular therapist at your child's school.

What happens afterwards?

If you wish, you will be sent the results of the study as soon as they become available which you will be able to discuss with your child's physiotherapist and/or doctor. The information

gained during this study may be published in a scientific journal or presented at a congress and shared with Physiotherapists and scientists at special interest meetings, without identifying any data of your child.

DECLARATION OF CONSENT

I....., hereby agree for my child.....to take part in the study entitled: "An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy".

I declare that:

I have read or had read to me this information and consent form and it is written in a language I am comfortable to use.

I have had a chance to ask any questions, and they were answered to my satisfaction.

Participation is entirely voluntary, and neither I nor my child, have not been pressurised into taking part.

I may withdraw my child from the study at any time without his / her future medical treatment being influenced whatsoever.

My child may be asked to leave the study before it has finished if his / her doctor or researcher feels it is in my child's best interests, or if my child is no longer interested in the agreed study plan.

Signed at.....on.....

.....

Signature of parent or legal guardian

DECLARATION OF INVESTIGATOR

I.....declare that:

I explained the information in the participant letter to .....

I encouraged him / her to ask questions and that I answered them appropriately and understandably.

I am satisfied that (s)he understands the study.

I did / did not use a translator.

Signed at.....on.....

.....

Signature of investigator

Appendix A 10: Informed assent / consent form for children with typical development (TD)

Name: ..... **Grade:** .....

Child Assent Form ***(for typically developing(TD) child)***

UNIVERSITY OF CAPE TOWN FACULTY OF HEALTH SCIENCES

PARTICIPANT INFORMATION LEAFLET AND ASSENT FORM

TITLE OF THE RESEARCH PROJECT:

An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy.

RESEARCHER'S NAME(S): Saviour Adjeuti **(HREC REF 490 / 2011)**

ADDRESS: University of Cape Town

Faculty of Health Science

Dept of Human Biology

CONTACT NUMBER: 078 065 2713

What is RESEARCH?

Research is something we do to find new knowledge about the way things (and people) work. We use research projects or studies to help us find out more about disease or illness. Research also helps us to find better ways of helping, or treating children who are sick and knowledge about healthy individuals such as you can help in giving understanding to mates, friends and relatives of our age group who are suffering from one bad condition or the other.

What is this research project all about?

This study wants to look at the 'inside' of your tummy muscle to see what is in them that is making them look stronger or weaker than those of your friends from schools with special needs who are not able to stand upright and walk properly. For us to be able to do this study, we will measure how tall you are and how much you weigh. By putting a probe on your tummy muscles – called ultrasound (*the same machine your mommy had to see what you looked like before you were born!)* while you are lying down and when you are standing to see how thick or thin your tummy muscles are. This will also be done when moving your leg and head forward while lying down and also your arm forward. We will measure how much your tummy muscles work inside you with another machine in contact with the skin of your tummy muscles (electromyograph –EMG). You *may* also be asked to lift small weights, take a rest and repeat it for about 10 to 15mins to enable us judge how your tummy muscles are made. You *may* be asked to walk on a carpet for a small machine to measure how you walk.

None of these tests will cause any pain, but if you are scared, you can just watch first when we do it on other friends of yours and you can also be allowed to do some practice first.

Why have I been invited to take part in this research project?

For those people who study the science of human beings, those who give treatment and care to children with spastic type cerebral palsy (STCP) and for doctors to help children with this condition (children who cannot stand or walk properly), they all need to know and understand very well how the 'inside' of tummy muscles of healthy children as you look like and how these tummy muscles work inside you. Whatever is seen and known from the study of healthy people like you can be compared with people of your age group who are suffering from STCP and cannot stand upright or walk properly like you do. So if you become part of this study, you will be giving your contribution to helping in the understanding and treatment of your friends and relatives who are suffering from this condition called STCP. Therefore, you are simply being asked to take part in this study because you are:

- physically fit,
- between 6 and 18 years of age and
- attend a school which is located close to school for children with special needs, where children with the condition are being recruited for the study.

Who is doing the research?

I am Saviour Adjenti, I used to teach medical and physiotherapy students about the human body in Accra, Ghana. Now I have registered for a higher degree at the University of Cape Town. I am doing this study so that I can get another certificate called PhD and also come out with some new findings that may help therapists/care-givers/doctors to improve on treatments that are being giving to your friends and relatives currently suffering from this condition.

Can anything bad happen to me?

Nothing bad can happen and should you hurt yourself by accident, the nurse will help you and I will phone your parents to tell them about it.

Can anything good happen to me?

Hopefully, depending on what we find, scientists, therapists/care-givers/doctors may use that to help make your friends who are suffering from the condition's tummy muscles get stronger and that may help them walk better, stand and sit more upright. Better understanding of the condition will make their care-givers also improve the balance these children with STCP through an enhanced treatment.

Will anyone know I am in the study?

Only myself, my research assistant, who is a physiotherapist and my study supervisors at the university will know that you are in the study. I will not use your name anywhere, so nobody will be able to know you took part. If you agree to it, I may want to use one of your photographs of the tummy muscles in an article to be published in a professional journal, but will not do so if you do not agree.

Who can I talk to about the study?

You can talk to me (078 065 2713). You can also talk to the human Research Ethics Committee of my university on (021 406 6626). You can also talk to any of my supervisors (Prof Louw 021- 406 6302, Prof Jelsma 021-406 6595 & Dr Unger 021-938 9302).

What if I do not want to do this?

You can change your mind at any time. It will not affect your schooling at all.

Do you understand this research study and are you willing to take part in it? **YES / NO**

Has the researcher answered all your questions? **YES / NO**

Do you understand that you can withdraw from the study at any time? **YES/ NO**

_____ _____

Signature of Child Date

Appendix A 11: Informed consent form for parents / guardians of child with typical development

Name of Child: ..... Grade: .....

ETHICAL CONSIDERATIONS – CONTROLS - *Typically Developing (TD child)*

Title of the project: An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy.

Principal investigator: Saviour Adjenti, MPhil Anatomy

Address: University of Cape Town, Faculty of Health Sciences, Department of Human Biology.

Parent / Guardian Assent Form

You and your child are being invited to take part in a research project. Please read the information in this letter, and feel free to ask the study staff about anything that is unclear to you. Participation is entirely voluntary, and your child's future in this school will not be negatively influenced if you decide not to take part. If you do agree to participate, you are free to withdraw from the study at any time without your child's education being jeopardised in any way.

Approval of this study is given by the Ethics Committee for Human Research at The Faculty of Health Sciences, University of Cape Town, and will be conducted according to the South African Guidelines for Good Clinical Practice and the Medical Research Council (MRC) Ethical Guidelines for Research. Permission from the Headmaster of your child's school as well as the Department of Education has been obtained.

What is the study about?

This study is to investigate the fine structure of the abdominal muscles of children with spastic type of cerebral palsy as seen in children with special needs in nearby schools (e.g EROS), using ultrasound imaging, electromyography, some form of X-ray (Lodox) and physical activities. The aim is to gather as much information as possible on the fine structure of the abdominal muscles in children with the condition using non-invasive means and then compare these results with those from children with typical development, such as your child in order to help therapists better understand the contribution of muscle strength or weakness in the tummy muscles to walking and balancing functions.

What do you need to do?

You may ask to be present during testing or attend any of the exercise sessions, however your assistance is not essential. Your child will be tested and take part in the exercise program during school hours in their free or break times. The tests include the following:

Your child's height and weight will be measured, and the thickness of your child's tummy muscles will be measured using ultrasound, which involves placing a probe on the skin over the tummy muscles of child's dominant/active side while he or she is lying down motionless. This measurement with the ultrasound machine will also be done while lying down and moving head forward, lying down and moving one leg up and also while he/ she is standing.

Surface electromyography, sEMG with probes fixed to the skin of the tummy muscles will measure the activity of the tummy muscles of your child during these postures. In addition, your child would also be asked to do small weight lifting exercise (according to his or her abilities) for about 15mins. Your child may also be asked to walk a short distance on a carpeted floor for a machine to measure how he/she walks. None of these tests will cause any pain, but should your child experience any anxiety or fear, (s)he can observe as well as have time to familiarize him/herself with all the tests. Results from your child are meant to be compared with those to be obtained from children with STCP in nearby schools for children with special needs, in order to make a fair judgement on what exactly is happening to the tummy muscles of those children (with STCP), for which reason they are unable to walk normally or stand up properly.

Why have you been invited to take part?

Results from a study on children with spastic type cerebral palsy (STCP) cannot be fully understood unless information is obtained from and compared with those of their aged-matched peers, such as your child, who are physically fit and without the condition (STCP). Therefore, your child has been invited to take part in this study because:

- he/she physically fit,
- he/she is between 6 and 18 years of age and
- attends a school which is located close to school for children with special needs, where children with the condition are being recruited for the study.

Will you benefit from taking part?

As the study does not involve any form of treatment, your child will therefore not benefit directly, however knowledge gained from this study should enable therapists to better understand the role of the trunk (abdominal) muscles in children and therefore contribute to

better decision-making regarding children with physical/motor problems. Neither you nor your child will be paid to take part in this study, nor will you incur any costs.

Are there any risks?

No known side effects or risks have been reported for the testing procedure that your child will undergo. No known allergic reactions to the gel, which serves as a contact medium for the head of the ultrasound machine, have ever been reported. Neither do the sEMG probe nor electrode placements except for a brief moment of a feeling of tingling sensation upon contact. Neither will the short walk on the carpet involve any pain nor fatigue as this will be done at child's own pace.

Will my child remain anonymous?

None of your child's personal details will be made known to anyone other than the research staff, and will not be published in any form. The data of your child will be stored and presented anonymously. All images and video recordings will be destroyed after completion of the study.

What happens if I have any questions?

You are welcome to address any questions to **Saviour Adjenti on 078 065 2713** at any time. You are also welcome to contact the Committee for Human Research of the Faculty of Health Sciences, University of Cape Town on **(021) 406 6338** if you have any questions, or complaints that have not been answered by the study staff.

What happens afterwards?

If you wish, you will be sent the results of the study as soon as they become available which you will be able to discuss with the primary researcher (Saviour Adjenti).

About the researcher

Saviour Adjenti is a former Human Anatomy lecturer of the Ghana Medical School, Accra and now a registered PhD student in the Department of Human Biology, Faculty of Health Sciences, University of Cape Town. He has an M.Phil degree in Human Anatomy and is doing this research with supervisions from one anatomist and two physiotherapy professors, one of whom is a regular therapist at a nearby school for children with special needs.

What happens afterwards?

If you wish, you will be sent the results of the study as soon as they become available which

you will be able to discuss with your child's physiotherapist and/or doctor. The information gained during this study may be published in a scientific journal or presented at a congress and shared with Physiotherapists and scientists at special interest meetings, without identifying any data of your child.

DECLARATION OF CONSENT

I,……., hereby agree for my child……..to take part in the study entitled: "An Investigation into the Ultrastructure of Abdominal Muscle Parameters and their Effect on Anterior Pelvic tilt in Children and Adolescents with Spastic Type Cerebral Palsy".

I declare that:

I have read or had read to me this information and consent form and it is written in a language I am comfortable to use.

I have had a chance to ask any questions, and they were answered to my satisfaction.

Participation is entirely voluntary, and neither I nor my child, have not been pressurised into taking part.

I may withdraw my child from the study at any time without his / her future medical treatment being influenced whatsoever.

My child may be asked to leave the study before it has finished if his / her doctor or researcher feels it is in my child's best interests, or if my child is no longer interested in the agreed study plan.

Signed at……on……

……

Signature of parent or legal guardian

DECLARATION OF INVESTIGATOR

I……declare that:

I explained the information in the participant letter to ……

I encouraged him / her to ask questions and that I answered them appropriately and understandably.

I am satisfied that (s)he understands the study.

I did / did not use a translator.

Signed at.....on.....

.....

Signature of investigator

NB: Some of the items in the original consent forms could not be carried out for various reasons but had to be amended slightly for other tests. See attached amended approval letters above.

Appendix B: GMFM tool and the interpretation of disability levels

Appendix B 1: The GMFM tool

GROSS MOTOR FUNCTION MEASURE (GMFM)
SCORE SHEET (GMFM-88 and GMFM-66 scoring)
Version 1.0

Child's Name: _____ ID #: _____

Assessment date: _____ year / month /day

Date of birth: _____ year / month /day

Chronological age: _____ years/months

Evaluator's Name: _____

GMFCS Level [1]

☐ I ☐ II ☐ III ☐ IV ☐ V

Testing Conditions (eg, room, clothing, time, others present)

_____

_____

The GMFM is a standardized observational instrument designed and validated to measure change in gross motor function over time in children with cerebral palsy. The scoring key is meant to be a general guideline. However, most of the items have specific descriptors for each score. It is imperative that the guidelines contained in the manual be used for scoring each item.

SCORING KEY
0 = does not initiate
1 = initiates
2 = partially completes
3 = completes
NT = Not tested [used for the GMAE scoring*]

It is now important to differentiate a true score of "0" (child does not initiate) from an item which is Not Tested (NT) if you are interested in using the GMFM-66 Ability Estimator Software.

*The GMFM-66 Gross Motor Ability Estimator (GMAE) software is available with the GMFM manual (2002). The advantage of the software is the conversion of the ordinal scale into an interval scale. This will allow for a more accurate estimate of the child's ability and provide a measure that is equally responsive to change across the spectrum of ability levels. Items that are used in the calculation of the GMFM-66 score are shaded and identified with an asterisk (*). The GMFM-66 is only valid for use with children who have cerebral palsy.

Contact for Research Group:
Dianne Russell, *CanChild* Centre for Childhood Disability Research, McMaster University, Institute for Applied Health Sciences, McMaster University, 1400 Main St. W., Rm. 408, Hamilton, L8S 1C7
Tel: North America - 1 905 525-9140 Ext: 27850
Tel: All other countries - 001 905 525-9140 Ext: 27850
E-mail: canchild@mcmaster.ca Fax: 1 905 522-6095
Website: www.fhs.mcmaster.ca/canchild

[1] GMFCS level is a rating of severity of motor function. Definitions are found in Appendix I of the GMFM manual (2002).

Check (√) the appropriate score: if an item is not tested (NT), circle the item number in the right column

	Item	A: LYING & ROLLING	SCORE				NT
	1.	SUP, HEAD IN MIDLINE: TURNS HEAD WITH EXTREMITIES SYMMETRICAL	0☐	1☐	2☐	3☐	1.
*	2.	SUP: BRINGS HANDS TO MIDLINE, FINGERS ONE WITH THE OTHER	0☐	1☐	2☐	3☐	2.
	3.	SUP: LIFTS HEAD 45°	0☐	1☐	2☐	3☐	3.
	4.	SUP: FLEXES R HIP AND KNEE THROUGH FULL RANGE	0☐	1☐	2☐	3☐	4.
	5.	SUP: FLEXES L HIP AND KNEE THROUGH FULL RANGE	0☐	1☐	2☐	3☐	5.
*	6.	SUP: REACHES OUT WITH R ARM, HAND CROSSES MIDLINE TOWARD TOY	0☐	1☐	2☐	3☐	6.
*	7.	SUP: REACHES OUT WITH L ARM, HAND CROSSES MIDLINE TOWARD TOY	0☐	1☐	2☐	3☐	7.
	8.	SUP: ROLLS TO PR OVER R SIDE	0☐	1☐	2☐	3☐	8.
	9.	SUP: ROLLS TO PR OVER L SIDE	0☐	1☐	2☐	3☐	9.
*	10.	PR: LIFTS HEAD UPRIGHT	0☐	1☐	2☐	3☐	10.
	11.	PR ON FOREARMS: LIFTS HEAD UPRIGHT, ELBOWS EXT., CHEST RAISED	0☐	1☐	2☐	3☐	11.
	12.	PR ON FOREARMS: WEIGHT ON R FOREARM, FULLY EXTENDS OPPOSITE ARM FORWARD	0☐	1☐	2☐	3☐	12.
	13.	PR ON FOREARMS: WEIGHT ON L FOREARM, FULLY EXTENDS OPPOSITE ARM FORWARD	0☐	1☐	2☐	3☐	13.
	14.	PR: ROLLS TO SUP OVER R SIDE	0☐	1☐	2☐	3☐	14.
	15.	PR: ROLLS TO SUP OVER L SIDE	0☐	1☐	2☐	3☐	15.
	16.	PR: PIVOTS TO R 90° USING EXTREMITIES	0☐	1☐	2☐	3☐	16.
	17.	PR: PIVOTS TO L 90° USING EXTREMITIES	0☐	1☐	2☐	3☐	17.
		TOTAL DIMENSION A	☐				

	Item	B: SITTING	SCORE				NT
*	18.	SUP, HANDS GRASPED BY EXAMINER: PULLS SELF TO SITTING WITH HEAD CONTROL	0☐	1☐	2☐	3☐	18.
	19.	SUP: ROLLS TO R SIDE, ATTAINS SITTING	0☐	1☐	2☐	3☐	19.
	20.	SUP: ROLLS TO L SIDE, ATTAINS SITTING	0☐	1☐	2☐	3☐	20.
*	21.	SIT ON MAT, SUPPORTED AT THORAX BY THERAPIST: LIFTS HEAD UPRIGHT, MAINTAINS 3 SECONDS	0☐	1☐	2☐	3☐	21.
*	22.	SIT ON MAT, SUPPORTED AT THORAX BY THERAPIST: LIFTS HEAD MIDLINE, MAINTAINS 10 SECONDS	0☐	1☐	2☐	3☐	22.
*	23.	SIT ON MAT, ARM(S) PROPPING: MAINTAINS, 5 SECONDS	0☐	1☐	2☐	3☐	23.
*	24.	SIT ON MAT: MAINTAINS, ARMS FREE, 3 SECONDS	0☐	1☐	2☐	3☐	24.
*	25.	SIT ON MAT WITH SMALL TOY IN FRONT: LEANS FORWARD, TOUCHES TOY, RE-ERECTS WITHOUT ARM PROPPING	0☐	1☐	2☐	3☐	25.
*	26.	SIT ON MAT: TOUCHES TOY PLACED 45° BEHIND CHILD'S R SIDE, RETURNS TO START	0☐	1☐	2☐	3☐	26.
*	27.	SIT ON MAT: TOUCHES TOY PLACED 45° BEHIND CHILD'S L SIDE, RETURNS TO START	0☐	1☐	2☐	3☐	27.
	28.	R SIDE SIT: MAINTAINS, ARMS FREE, 5 SECONDS	0☐	1☐	2☐	3☐	28.
	29.	L SIDE SIT: MAINTAINS, ARMS FREE, 5 SECONDS	0☐	1☐	2☐	3☐	29.
*	30.	SIT ON MAT: LOWERS TO PR WITH CONTROL	0☐	1☐	2☐	3☐	30.
*	31.	SIT ON MAT WITH FEET IN FRONT: ATTAINS 4 POINT OVER R SIDE	0☐	1☐	2☐	3☐	31.
*	32.	SIT ON MAT WITH FEET IN FRONT: ATTAINS 4 POINT OVER L SIDE	0☐	1☐	2☐	3☐	32.
	33.	SIT ON MAT: PIVOTS 90°, WITHOUT ARMS ASSISTING	0☐	1☐	2☐	3☐	33.
*	34.	SIT ON BENCH: MAINTAINS, ARMS AND FEET FREE, 10 SECONDS	0☐	1☐	2☐	3☐	34.
*	35.	STD: ATTAINS SIT ON SMALL BENCH	0☐	1☐	2☐	3☐	35.
*	36.	ON THE FLOOR: ATTAINS SIT ON SMALL BENCH	0☐	1☐	2☐	3☐	36.
*	37.	ON THE FLOOR: ATTAINS SIT ON LARGE BENCH	0☐	1☐	2☐	3☐	37.
		TOTAL DIMENSION B	☐				

Item		C: CRAWLING & KNEELING	SCORE	NT
	38.	PR: CREEPS FORWARD 1.8m (6')	0 ☐ 1 ☐ 2 ☐ 3 ☐	38.
*	39.	4 POINT: MAINTAINS, WEIGHT ON HANDS AND KNEES, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	39.
*	40.	4 POINT: ATTAINS SIT ARMS FREE	0 ☐ 1 ☐ 2 ☐ 3 ☐	40.
*	41.	PR: ATTAINS 4 POINT, WEIGHT ON HANDS AND KNEES	0 ☐ 1 ☐ 2 ☐ 3 ☐	41.
*	42.	4 POINT: REACHES FORWARD WITH R ARM, HAND ABOVE SHOULDER LEVEL	0 ☐ 1 ☐ 2 ☐ 3 ☐	42.
*	43.	4 POINT: REACHES FORWARD WITH L ARM, HAND ABOVE SHOULDER LEVEL	0 ☐ 1 ☐ 2 ☐ 3 ☐	43.
*	44.	4 POINT: CRAWLS OR HITCHES FORWARD 1.8m (6')	0 ☐ 1 ☐ 2 ☐ 3 ☐	44.
*	45.	4 POINT: CRAWLS RECIPROCALLY FORWARD 1.8m (6')	0 ☐ 1 ☐ 2 ☐ 3 ☐	45.
*	46.	4 POINT: CRAWLS UP 4 STEPS ON HANDS AND KNEES/FEET	0 ☐ 1 ☐ 2 ☐ 3 ☐	46.
	47.	4 POINT: CRAWLS BACKWARDS DOWN 4 STEPS ON HANDS AND KNEES/FEET	0 ☐ 1 ☐ 2 ☐ 3 ☐	47.
*	48.	SIT ON MAT: ATTAINS HIGH KN USING ARMS, MAINTAINS, ARMS FREE, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	48.
	49.	HIGH KN: ATTAINS HALF KN ON R KNEE USING ARMS, MAINTAINS, ARMS FREE, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	49.
	50.	HIGH KN: ATTAINS HALF KN ON L KNEE USING ARMS, MAINTAINS, ARMS FREE, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	50.
*	51.	HIGH KN: KN WALKS FORWARD 10 STEPS, ARMS FREE	0 ☐ 1 ☐ 2 ☐ 3 ☐	51.

TOTAL DIMENSION C ☐

Item		D: STANDING	SCORE	NT
*	52.	ON THE FLOOR: PULLS TO STD AT LARGE BENCH	0 ☐ 1 ☐ 2 ☐ 3 ☐	52.
*	53.	STD: MAINTAINS, ARMS FREE, 3 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	53.
*	54.	STD: HOLDING ON TO LARGE BENCH WITH ONE HAND, LIFTS R FOOT, 3 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	54.
*	55.	STD: HOLDING ON TO LARGE BENCH WITH ONE HAND, LIFTS L FOOT, 3 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	55.
*	56.	STD: MAINTAINS, ARMS FREE, 20 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	56.
*	57.	STD: LIFTS L FOOT, ARMS FREE, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	57.
*	58.	STD: LIFTS R FOOT, ARMS FREE, 10 SECONDS	0 ☐ 1 ☐ 2 ☐ 3 ☐	58.
*	59.	SIT ON SMALL BENCH: ATTAINS STD WITHOUT USING ARMS	0 ☐ 1 ☐ 2 ☐ 3 ☐	59.
*	60.	HIGH KN: ATTAINS STD THROUGH HALF KN ON R KNEE, WITHOUT USING ARMS	0 ☐ 1 ☐ 2 ☐ 3 ☐	60.
*	61.	HIGH KN: ATTAINS STD THROUGH HALF KN ON L KNEE, WITHOUT USING ARMS	0 ☐ 1 ☐ 2 ☐ 3 ☐	61.
*	62.	STD: LOWERS TO SIT ON FLOOR WITH CONTROL, ARMS FREE	0 ☐ 1 ☐ 2 ☐ 3 ☐	62.
*	63.	STD: ATTAINS SQUAT, ARMS FREE	0 ☐ 1 ☐ 2 ☐ 3 ☐	63.
*	64.	STD: PICKS UP OBJECT FROM FLOOR, ARMS FREE, RETURNS TO STAND	0 ☐ 1 ☐ 2 ☐ 3 ☐	64.

TOTAL DIMENSION D ☐

Item		E: WALKING, RUNNING & JUMPING	SCORE				NT
*	65.	STD, 2 HANDS ON LARGE BENCH: CRUISES 5 STEPS TO R	0 ☐	1 ☐	2 ☐	3 ☐	65.
*	66.	STD, 2 HANDS ON LARGE BENCH: CRUISES 5 STEPS TO L	0 ☐	1 ☐	2 ☐	3 ☐	66.
*	67.	STD, 2 HANDS HELD: WALKS FORWARD 10 STEPS	0 ☐	1 ☐	2 ☐	3 ☐	67.
*	68.	STD, 1 HAND HELD: WALKS FORWARD 10 STEPS	0 ☐	1 ☐	2 ☐	3 ☐	68.
*	69.	STD: WALKS FORWARD 10 STEPS	0 ☐	1 ☐	2 ☐	3 ☐	69.
*	70.	STD: WALKS FORWARD 10 STEPS, STOPS, TURNS 180°, RETURNS	0 ☐	1 ☐	2 ☐	3 ☐	70.
*	71.	STD: WALKS BACKWARD 10 STEPS	0 ☐	1 ☐	2 ☐	3 ☐	71.
*	72.	STD: WALKS FORWARD 10 STEPS, CARRYING A LARGE OBJECT WITH 2 HANDS	0 ☐	1 ☐	2 ☐	3 ☐	72.
*	73.	STD: WALKS FORWARD 10 CONSECUTIVE STEPS BETWEEN PARALLEL LINES 20cm (8") APART	0 ☐	1 ☐	2 ☐	3 ☐	73.
*	74.	STD: WALKS FORWARD 10 CONSECUTIVE STEPS ON A STRAIGHT LINE 2cm (3/4") WIDE	0 ☐	1 ☐	2 ☐	3 ☐	74.
*	75.	STD: STEPS OVER STICK AT KNEE LEVEL, R FOOT LEADING	0 ☐	1 ☐	2 ☐	3 ☐	75.
*	76.	STD: STEPS OVER STICK AT KNEE LEVEL, L FOOT LEADING	0 ☐	1 ☐	2 ☐	3 ☐	76.
*	77.	STD: RUNS 4.5m (15'), STOPS & RETURNS	0 ☐	1 ☐	2 ☐	3 ☐	77.
*	78.	STD: KICKS BALL WITH R FOOT	0 ☐	1 ☐	2 ☐	3 ☐	78.
*	79.	STD: KICKS BALL WITH L FOOT	0 ☐	1 ☐	2 ☐	3 ☐	79.
*	80.	STD: JUMPS 30cm (12") HIGH, BOTH FEET SIMULTANEOUSLY	0 ☐	1 ☐	2 ☐	3 ☐	80.
*	81.	STD: JUMPS FORWARD 30 cm (12"), BOTH FEET SIMULTANEOUSLY	0 ☐	1 ☐	2 ☐	3 ☐	81.
*	82.	STD ON R FOOT: HOPS ON R FOOT 10 TIMES WITHIN A 60cm (24") CIRCLE	0 ☐	1 ☐	2 ☐	3 ☐	82.
*	83.	STD ON L FOOT: HOPS ON L FOOT 10 TIMES WITHIN A 60cm (24") CIRCLE	0 ☐	1 ☐	2 ☐	3 ☐	83.
*	84.	STD, HOLDING 1 RAIL: WALKS UP 4 STEPS, HOLDING 1 RAIL, ALTERNATING FEET	0 ☐	1 ☐	2 ☐	3 ☐	84.
*	85.	STD, HOLDING 1 RAIL: WALKS DOWN 4 STEPS, HOLDING 1 RAIL, ALTERNATING FEET	0 ☐	1 ☐	2 ☐	3 ☐	85.
*	86.	STD: WALKS UP 4 STEPS, ALTERNATING FEET	0 ☐	1 ☐	2 ☐	3 ☐	86.
*	87.	STD: WALKS DOWN 4 STEPS, ALTERNATING FEET	0 ☐	1 ☐	2 ☐	3 ☐	87.
*	88.	STD ON 15cm (6") STEP: JUMPS OFF, BOTH FEET SIMULTANEOUSLY	0 ☐	1 ☐	2 ☐	3 ☐	88.

TOTAL DIMENSION E ☐

Was this assessment indicative of this child's "regular" performance? YES ☐ NO ☐

COMMENTS:

GMFM RAW SUMMARY SCORE

DIMENSION	CALCULATION OF DIMENSION % SCORES	GOAL AREA (indicated with ✓ check)
A. Lying & Rolling	$\frac{\text{Total Dimension A}}{51} = \frac{\quad}{51} \times 100 = \quad\%$	A. ☐
B. Sitting	$\frac{\text{Total Dimension B}}{60} = \frac{\quad}{60} \times 100 = \quad\%$	B. ☐
C. Crawling & Kneeling	$\frac{\text{Total Dimension C}}{42} = \frac{\quad}{42} \times 100 = \quad\%$	C. ☐
D. Standing	$\frac{\text{Total Dimension D}}{39} = \frac{\quad}{39} \times 100 = \quad\%$	D. ☐
E. Walking, Running & Jumping	$\frac{\text{Total Dimension E}}{72} = \frac{\quad}{72} \times 100 = \quad\%$	E. ☐

TOTAL SCORE = $\frac{\%A + \%B + \%C + \%D + \%E}{\text{Total \# of Dimensions}}$

$= \frac{\quad + \quad + \quad + \quad + \quad}{5} = \frac{\quad}{5} = \quad\%$

GOAL TOTAL SCORE = $\frac{\text{Sum of \% scores for each dimension identified as a goal area}}{\text{\# of Goal areas}}$

$= \quad = \quad\%$

GMFM-66 Gross Motor Ability Estimator Score [1]

GMFM-66 Score = _____ _____ to _____ 95% Confidence Intervals

previous GMFM-66 Score = _____ _____ to _____ 95% Confidence Intervals

change in GMFM-66 = _____

[1] from the Gross Motor Ability Estimator (GMAE) Software

TESTING WITH AIDS/ORTHOSES

Indicate below with a check (✓) which aid/orthosis was used and what dimension it was first applied. (There may be more than one).

AID		DIMENSION	ORTHOSIS		DIMENSION
Rollator/Pusher	☐	____	Hip Control	☐	____
Walker	☐	____	Knee Control	☐	____
H Frame Crutches	☐	____	Ankle-Foot Control	☐	____
Crutches	☐	____	Foot Control	☐	____
Quad Cane	☐	____	Shoes	☐	____
Cane	☐	____	None	☐	____
None	☐	____	Other	☐	____
Other	☐	____			

_____ (please specify)

_____ (please specify)

RAW SUMMARY SCORE USING AIDS/ORTHOSES

DIMENSION	CALCULATION OF DIMENSION % SCORES	GOAL AREA (indicated with ✓ check)
F. Lying & Rolling	$\frac{\text{Total Dimension A}}{51} = \frac{\_\_\_\_}{51} \times 100 = \_\_\_\_\_ \%$	A. ☐
G. Sitting	$\frac{\text{Total Dimension B}}{60} = \frac{\_\_\_\_}{60} \times 100 = \_\_\_\_\_ \%$	B. ☐
H. Crawling & Kneeling	$\frac{\text{Total Dimension C}}{42} = \frac{\_\_\_\_}{42} \times 100 = \_\_\_\_\_ \%$	C. ☐
I. Standing	$\frac{\text{Total Dimension D}}{39} = \frac{\_\_\_\_}{39} \times 100 = \_\_\_\_\_ \%$	D. ☐
J. Walking, Running & Jumping	$\frac{\text{Total Dimension E}}{72} = \frac{\_\_\_\_}{72} \times 100 = \_\_\_\_\_ \%$	E. ☐

TOTAL SCORE = $\frac{\%A + \%B + \%C + \%D + \%E}{\text{Total \# of Dimensions}}$

$= \frac{\_\_\_ + \_\_\_ + \_\_\_ + \_\_\_ + \_\_\_}{5} = \frac{\_\_\_\_}{5} = \_\_\_\_\_ \%$

GOAL TOTAL SCORE = $\frac{\text{Sum of \% scores for each dimension identified as a goal area}}{\text{\# of Goal areas}}$

$= \_\_\_\_\_ = \_\_\_\_\_ \%$

GMFM-66 Gross Motor Ability Estimator Score [1]

GMFM-66 Score = _____ _____ to _____ 95% Confidence Intervals

previous GMFM-66 Score = _____ _____ to _____ 95% Confidence Intervals

change in GMFM-66 = _____

[1] from the Gross Motor Ability Estimator (GMAE) Software

Appendix B 2: Interpretation of GMFCS Levels

GENERAL HEADINGS FOR EACH LEVEL

LEVEL I	-	Walks without Limitations
LEVEL II	-	Walks with Limitations
LEVEL III	-	Walks Using a Hand-Held Mobility Device
LEVEL IV	-	Self-Mobility with Limitations; May Use Powered Mobility
LEVEL V	-	Transported in a Manual Wheelchair

DISTINCTIONS BETWEEN LEVELS

Distinctions Between Levels I and II - Compared with children and youth in Level I, children and youth in Level II have limitations walking long distances and balancing; may need a hand-held mobility device when first learning to walk; may use wheeled mobility when traveling long distances outdoors and in the community; require the use of a railing to walk up and down stairs; and are not as capable of running and jumping.

Distinctions Between Levels II and III - Children and youth in Level II are capable of walking without a hand-held mobility device after age 4 (although they may choose to use one at times). Children and youth in Level III need a hand-held mobility device to walk indoors and use wheeled mobility outdoors and in the community.

Distinctions Between Levels III and IV - Children and youth in Level III sit on their own or require at most limited external support to sit, are more independent in standing transfers, and walk with a hand-held mobility device. Children and youth in Level IV function in sitting (usually supported) but self-mobility is limited. Children and youth in Level IV are more likely to be transported in a manual wheelchair or use powered mobility.

Distinctions Between Levels IV and V - Children and youth in Level V have severe limitations in head and trunk control and require extensive assisted technology and physical assistance. Self-mobility is achieved only if the child/youth can learn how to operate a powered wheelchair.

Appendix C: Intra-and inter-rater tests

Appendix C 1: Intra-rater reliability measurements

Intra-rater reliability measurements

Background

The ability of an examiner to perform accurately a specific testing method repeatedly is referred to as intra-rater reliability measurement. It forms part of standard measurement procedures in research as independent investigators commonly follow test methods to re-evaluate the validity of a particular test.

Aim

The aim of this feasibility study was to establish the reliability of the tests used in the main study.

Specific objectives

The specific objectives of this feasibility study were to determine:

- Intra-rater reliability of anthropometric measurements
- Intra-rater reliability of ultrasound measurements for each of the four abdominal muscles during the resting and active states for both groups
- Intra-rater reliability of sEMG measurements for each of the four abdominal muscles during the resting and active states for both groups
- Intra-rater reliability of GMFM scores
- Intra-rater reliability of PCI measurements both groups

Participants

For each of the test involving BMI, US and sEMG measurements, fifteen participants each for the STCP and TD group were recruited. While for each of the PCI and GMFM tests, twenty individuals in each group took part in the study.

Testing procedure

Testing was done as reported in chapter 3 of the main study.

Measurements

- Anthropometric: Height (cm) and weight (kg) while BMI was calculated by Excel® using the results of height and weight.

- Ultrasound measurements: muscle thickness was measured using the electronic calliper. Pennation angle was measured by ImageJ software while fibre length was calculated from the results of muscle thickness and pennation angle.
- sEMG activity was measured during resting and contracted states.
- PCI was calculated for each child.
- GMFM calculated and expressed as a percentage.

Statistical analysis

Data were analysed using Statistica version 11. Typical error of measurements and intra-class co-efficient were assessed and reported with their respective 95% confidence intervals. All the data were presented below as the mean ± standard deviations:

Appendix C 1: Table 1: Intra-tester reliability of ultrasound measurements for EO in the feasibility study for the STCP group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
EO Th R	0.92 (0.68 – 1.72)	0.94 (0.80 – 0.98)	0.36
EO Th Ac	0.85 (0.62 – 1.59)	0.98 (0.92 – 0.99)	0.32
EO PA R	0.99 (0.72 – 1.84)	0.98 (0.93 – 0.99)	0.15
EO PA Ac	0.92 (0.67 – 1.71)	0.88 (0.76 – 0.90)	0.18
EO FL R	0.88 (0.64 – 1.60)	0.90 (0.85 – 0.95)	0.30
EO FL Ac	0.90 (0.66 – 1.74)	0.94 (0.92 – 0.96)	0.27

Appendix C 1: Table 2: Intra-tester reliability of ultrasound measurements for IO in the feasibility study for the STCP group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
IO Th R	0.89(0.66 – 0.96)	0.85 (0.61 – 0.95)	0.30
IO Th Ac	0.88(0.68 – 0.96)	0.87 (0.65 – 0.96)	0.22
IO PA R	0.74 (0.33 -0.91)	0.76 (0.41 – 0.91)	0.15
IO PA Ac	0.92 (0.67 – 1.71)	0.88 (0.76 – 0.90)	0.14
IO FL R	0.89 (0.69 – 0.96)	0.90 (0.85 – 0.95)	0.22
IO FL Ac	0.90 (0.66 – 1.74)	0.89 (0.68 – 0.96)	0.20

Appendix C 1: Table 3: Intra-tester reliability of ultrasound measurements for TrA in the feasibility study for the STCP group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
TrA Th R	0.83 (0.56 – 0.94)	0.83 (0.56 – 0.94)	0.38
TrA Th Ac	0.85 (0.62 – 1.59)	0.80 (0.49 – 0.93)	0.32
TrA PA R	0.80 (0.49 – 0.84)	0.86 (0.60 – 0.96)	0.17
TrA PA Ac	0.86 (0.60 – 0.96)	0.87 (0.61 – 0.90)	0.16
TrA FL R	0.87 (0.61 – 0.96)	0.89 (0.65 – 0.95)	0.32
TrA FL Ac	0.90 (0.66 – 1.74)	0.85 (0.68 – 0.96)	0.30

Appendix C 1: Table 4: Intra-tester reliability of ultrasound measurements for RA in the feasibility study for the STCP group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
RA Th R	0.92 (0.68 – 1.72)	0.94 (0.80 – 0.98)	0.76
RA Th Ac	0.85 (0.62 – 1.59)	0.98 (0.92 – 0.99)	0.79

Appendix C 1: Table 5: Intra-tester reliability of ultrasound measurements for EO in the feasibility study for the TD group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
EO Th R	0.87 (0.61 – 0.96)	0.91 (0.72 – 0.98)	0.27
EO Th Ac	0.85 (0.62 – 0.97)	0.91 (073 – 0.97)	0.32
EO PA R	0.93 (0.78 – 0.98)	0.95 (0.84 – 0.99)	0.24
EO PA Ac	0.92 (0.67 – 0.99)	0.93 (0.78 – 0.98)	0.21
EO FL R	0.88 (0.60 – 0.95)	0.90 (0.85 – 0.95)	0.30
EO FL Ac	0.89 (0.68 – 0.96)	0.92 (0.76 – 0.97)	0.27

Appendix C 1: Table 6: Intra-tester reliability of ultrasound measurements for IO in the feasibility study for the TD group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
IO Th R	0.89(0.66 – 0.96)	0.92 (0.76 – 0.97)	0.23
IO Th Ac	0.88(0.68 – 0.96)	0.91 (0.73 – 0.96)	0.22
IO PA R	0.74 (0.33 -0.91)	0.76 (0.41 – 0.91)	0.15
IO PA Ac	0.76 (0.41 – 0.91)	0.77 (0.37 – 0.90)	0.14
IO FL R	0.89 (0.69 – 0.96)	0.81 (045 – 0.95)	0.55
IO FL Ac	0.88 (0.61 – 0.97)	0.85 (0.60 – 0.95)	0.62

Appendix C 1: Table 7: Intra-tester reliability of ultrasound measurements for TrA in the feasibility study for the TD group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
TrA Th R	0.82 (0.49 – 0.95)	0.81 (0.45 – 0.94)	0.33
TrA Th Ac	0.85 (0.62 – 1.59)	0.77 (0.41 – 0.92)	0.32
TrA PA R	0.80 (0.49 – 0.84)	0.93 (0.78 – 0.98)	0.17
TrA PA Ac	0.86 (0.60 – 0.96)	0.87 (0.61 – 0.90)	0.16
TrA FL R	0.87 (0.61 – 0.96)	0.85 (0.48 – 0.95)	0.32
TrA FL Ac	0.90 (0.66 – 1.74)	0.85 (0.60 – 0.96)	0.62

Appendix C 1: Table 8: Intra-tester reliability of ultrasound measurements for RA in the feasibility study for the TD group (N = 15)

US measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
RA Th R	0.82 (0.48 – 0.72)	0.94 (0.80 – 0.98)	0.45
RA Th Ac	0.89 (0.71 – 0.96)	0.98 (0.92 – 0.99)	0.51

Appendix C 1: Table 9: Intra-tester reliability of EMG measurements in the feasibility study for the STCP group (N = 15)

EMG measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
EO EMG R	0.91 (0.68 – 0.97)	0.87 (0.65 – 0.96)	0.23
EO EMG Ac	0.89 (0.71 – 0.96)	0.89 (0.66 – 0.96)	0.22
IO EMG R	0.91 (0.72 – 0.97)	0.88 (0.68 – 0.94)	0.15
IO EMG Ac	0.81 (0.67 – 0.96)	0.80 (0.49 – 0.93)	0.14
RA EMG R	0.88 (0.64 – 0.96)	0.86 (0.60 – 0.95)	0.43
RA EMG Ac	0.90 (0.66 – 0.95)	0.87 (0.61 – 0.96)	0.42

Appendix C 1: Table 10: Intra-tester reliability of EMG measurements in the feasibility study for the TD group (N = 15)

EMG measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
EO EMG R	0.92 (0.80 – 0.94)	0.93 (0.78 – 0.98)	0.28
EO EMG Ac	0.88 (0.62 – 0.96)	0.89 (0.71 – 0.96)	0.32
IO EMG R	0.85 (0.60 – 0.95)	0.82 (0.49 – 0.95)	0.20
IO EMG Ac	0.86 (0.60 – 0.96)	0.85 (0.48 – 0.96)	0.21
RA EMG R	0.80 (0.49 – 0.93)	0.78 (0.45 – 0.91)	0.32
RA EMG Ac	0.81 (0.45 – 0.94)	0.79 (0.52 – 0.94)	0.30

Appendix C 1: Table 11: Intra-tester reliability of PCI measurements in the feasibility study for the STCP and TD groups (N = 20; STCP; N = 10: TD; N = 10)

PCI	Typical error 95 % CI	ICC 95% CI	Mean SD
STCP	0.76 (0.40 – 0.92)	0.82 (0.49 – 0.95)	0.30
TD	0.73 (0.37 – 0.91)	0.85 (0.48 – 0.96)	0.32

Appendix C 1: Table 12: Intra-tester reliability of GMFM measurements in the feasibility study for the STCP group (N = 20, 5 in each disability level)

GMFM test	Typical error 95 % CI	ICC 95% CI	Mean SD
GMFCS I	0.89 (0.66 – 0.96)	0.83 (0.56 – 0.94)	0.30
GMFCS II	0.85 (0.68 – 0.96)	0.80 (0.49 – 0.93)	0.22
GMFCS III	0.74 (0.63 – 0.93)	0.86 (0.60 – 0.96)	0.15
GMFCS IV	0.89 (0.69 – 0.95)	0.87 (0.61 – 0.95)	0.14

Appendix C 1: Table 13: Intra-tester reliability of anthropometric measurements (height, weight & BMI) in the feasibility study for the STCP group (N = 15)

Anthropometric measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
Height	0.85 (0.60 – 0.95)	0.94 (0.80 – 0.98)	0.38
Weight	0.88 (0.62 – 0.99)	0.98 (0.92 – 0.99)	0.32
BMI	0.81 (0.61 – 0.97)	0.76 (0.31 – 0.91)	0.20

Appendix C 1: Table 14: Intra-tester reliability of anthropometric measurements (height, weight & BMI) in the feasibility study for the TD group (N = 15)

Anthropometric measurements	Typical error 95 % CI	ICC 95% CI	Mean SD
Height	0.83 (0.46 – 094)	0.76 (0.40 – 0.92)	0.30
Weight	0.77 (0.41 – 0.92)	0.74 (0.33 – 0.91)	0.22
BMI	0.80 (0.49 – 0.93)	0.77 (0.41 – 0.92)	0.20

Appendix C 2: Inter-tester reliability

The aim of this testing procedure was for an independent investigator to test the validity of the instrumentations and the procedures used by the PI.

After a week of testing, the PI repeated the procedures for 15 or 20 participants (depending on type of test) while the assistant researchers (AR) also sampled similar numbers in both groups and performed the same procedures repeatedly. The results obtained by both the PI and AR were analysed using STATISTICA version 11 and presented in the tables below:

Appendix C 2: Table 1: Inter-rater test for measurement of muscle thickness (Th) during resting stage between PI and AR (STCP; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO Th R (mm)	3.5 ± 0.2	4.0 ± 0.2	- 0.5	0.15	0.94 (0.58 – 0.98)	0.86
IO Th R (mm)	5.0 ± 0.5	5.0 ± 0.5	0.0	0.18	0.96 (0.52 -0.96)	0.87
TrA Th R (mm)	2.8 ± 0.4	3.0 ± 0.5	- 0.2	0.23	0.95 (0.65 – 0.99)	0.87
RA Th R (mm)	6.0 ± 0.2	6.5 ± 0.4	- 0.5	0.20	0.93 (0.60 – 0.97)	0.79

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 2: Inter-rater test for measurement of muscle thickness (Th) during active stage between PI and AR (STCP; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM

EO Th Ac(mm)	3.0 ± 0.4	3.5 ± 0.5	- 0.5	0.13	0.96 (0.60 – 0.98)	0.66
IO Th Ac (mm)	4.6 ± 0.5	4.6 ± 0.8	0.0	0.20	0.95 (0.41 – 0.92)	0.58
TrA Th Ac (mm)	2.5 ± 0.5	2.8 ± 0.5	- 0.3	0.18	0.94 (0.68 – 0.98)	0.58
RA Th Ac (mm)	6.4 ± 0.5	6.8 ± 0.4	- 0.4	0.12	0.92 (0.62 – 0.99)	0.51

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 3: Inter-rater test for measurement of muscle thickness (Th) during resting stage between PI and AR (TD; N = 15)

	PI	**AR**	**Diff**	**SD Diff**	**ICC (95% CI)**	**SEM**
EO Th R(mm)	3.0 ± 0.2	3.2 ± 0.3	- 0.2	0.40	0.90 (0.88 – 0.94)	0.61
IO Th R (mm)	4.0 ± 0.1	4.0 ± 0.2	0.0	0.31	0.87 (0.62 – 0.92)	0.58
TrA Th R (mm)	2.0 ± 0.2	2.2 ± 0.3	- 0.2	0.45	0.85 (0.63 – 0.95)	0.60
RA Th R (mm)	6.0 ± 0. 3	6.3 ± 0.2	-0.3	0.39	0.86 (0.60 – 0.90)	0.56

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 4: Inter-rater test for measurement of muscle thickness (Th) during active stage between PI and AR (TD; N = 15)

	PI	**AR**	**Diff**	**SD Diff**	**ICC (95% CI)**	**SEM**

EO Th Ac(mm)	3.2 ± 0.3	3.5 ± 0.2	- 0.3	0.39	0.92 (0.80 – 0.94)	0.58
IO Th Ac (mm)	4.3 ± 0.2	4.3 ± 1.3	0.0	0.32	0.88 (0.62 – 0.96)	0.62
TrA Th Ac (mm)	2.2 ± 0.2	2.4 ± 0.2	- 0.2	0.43	0.86 (0.64 – 0.95)	0.61
RA Th Ac (mm)	6.4 ± 0.1	6.4 ± 0.2	0.0	0.45	0.85(0.60 – 0.96)	0.60

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 5: Inter-rater test for measurement of pennation angle (PA) during resting stage between PI and AR (STCP; N = 15)

	PI	**AR**	**Diff**	**SD Diff**	**ICC (95% CI)**	**SEM**
EO PA R(°)	2.0 ± 0.2	2.2 ± 0.3	-0.2	0.13	0.93 (0.76 – 0.97)	0.97
IO PA R(°)	2.3 ± 0.2	2.2 ± 0.2	-0.1	0.28	0.89 (0.66 – 0.96)	0.81
TrA PA R (°)	1.5 ± 0.5	1.6 ± 0.4	-0.1	0.22	0.85 (0.53 – 0.94)	0.57

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 6: Inter-rater test for measurement of pennation angle (PA) during active stage between PI and AR (STCP; N = 15)

	PI	**AR**	**Diff**	**SD Diff**	**ICC (95% CI)**	**SEM**
EO PA Ac (°)	1.8 ± 0.5	2.2 ± 0.2	- 0.4	0.18	0.90 (0.78 – 0.96)	1.10
IO PA Ac (°)	2.0 ± 0.3	2.2 ± 0.2	-0.2	0.32	0.91 (0.79 – 0.96)	0.79
TrA PA Ac (°)	1.5 ± 0.5	1.5 ± 0.5	0.0	0.25	0.94 (0.87 – 0.98)	0.60

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 7: Inter-rater test for measurement of pennation angle (PA) during resting stage between PI and AR (TD; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO PA R (°)	1.6 ± 0.2	1.6 ± 0.2	0.0	0.39	0.95 (0.65 – 0.99)	0.58
IO PA R (°)	2.0 ± 0.2	2.1 ± 0.4	-0.1	0.32	0.93 (0.60 – 0.97)	0.62
TrA PA R (°)	1.4 ± 0.2	1.5 ± 0.2	-0.1	0.43	0.92 (0.80 – 0.94)	0.61

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 8: Inter-rater test for measurement pennation angle (PA) during active stage between PI and AR (TD; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO PA Ac (°)	1.8 ± 0.2	1.8 ± 0.2	0.0	0.35	0.94 (0.58 – 0.98)	0.53
IO PA Ac (°)	2.2 ± 0.2	2.3 ± 0.3	-0.1	0.44	0.96 (0.52 -0.96)	0.60
TrA PA Ac (°)	1.5 ± 0.3	1.6 ± 0.2	-0.1	0. 38	0.95 (0.65 – 0.99)	0.65

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 9: Inter-rater test for measurement of muscle fibre length (FL) during resting stage between PI and AR (STCP; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO FL R (mm)	112 ± 2.2	114 ± 2.0	-2.0	10.4	0.87 (0.62 – 0.92)	0.77
IO FL R (mm)	130 ± 1.5	130 ± 2.0	0.0	13.6	0.85 (0.63 – 0.95)	0.86
TrA FL R (mm)	102 ± 2.0	102 ± 2.0	0.0	18.1	0.86 (0.60 – 0.90)	0.48

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 10: Inter-rater test for measurement of muscle fibre length (FL) during active stage between PI and AR (STCP; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO FL Ac (mm)	105 ± 2.0	106 ± 1.8	-1.0	12.8	0.86 (0.60 – 0.90)	0.78
IO FL Ac (mm)	125 ± 1.8	126 ± 2.0	-1.0	14.0	0.85 (0.53 – 0.94)	0.81
TrA FL Ac (mm)	96 ± 2.0	97 ± 2.0	-1.0	15.3	0.88 (0.62 – 0.96)	0.50

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 11: Inter-rater test for measurement of muscle fibre length (FL) during resting stage between PI and AR (TD; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO FL R (mm)	110 ± 2.0	112 ± 2.0	-2.0	16.2	0.87 (0.62 – 0.92)	0.72
IO FL R (mm)	127 ± 2.0	128 ± 1.8	-1.0	18.4	0.85(0.60 – 0.96)	0.82
TrA FL R (mm)	104 ± 2.0	105 ± 1.8	-1.0	22.0	0.87 (0.62 – 0.92)	0.46

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 12: Inter-rater test for measurement of muscle fibre length (FL) during active stage between PI and AR (TD; N = 15)

	PI	AR	Diff	SD Diff	ICC (95% CI)	SEM
EO FL Ac (mm)	104 ± 0.8	105 ± 1.0	-1.0	15.0	0.88 (0.62 – 0.96)	0.76
IO FL Ac (mm)	120 ± 1.0	121 ± 1.0	-1.0	18.8	0.86 (0.64 – 0.95)	0.85
TrA FL Ac (mm)	103 ± 1.0	103 ± 0.8	0.0	21.4	0.85(0.60 – 0.96)	0.43

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 13: Inter-rater test for sEMG activity during resting stage between PI and AR (STCP; N = 15)

Muscle	PI / Hz	AR / Hz	Diff	SD diff	ICC (95% CI)	SEM
EO	85.0 ± 0.5	86 ± 0.8	-1.0	2.1	0.96 (0.89 – 0.98)	1.13
IO	90.0 ± 1.0	92 ± 1.2	-2.0	1.5	0.89 (0.87 – 0.92	0.78
RA	11.5 ± 0.8	12 ± 1.0	-0.5	2.3	0.92 (0.90 – 0.96)	0.65

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 14: Inter-rater test for sEMG activity during the active stage between PI and AR (STCP; N = 15)

Muscle	PI / Hz	AR / Hz	Diff	SD diff	ICC (95% CI)	SEM
EO	108 ± 2.0	110 ± 2.0	-1.00	1.7	0.93 (0.76 – 0.97)	0.78
IO	128 ± 1.2	128 ± 1.5	-2.00	1.2	0.89 (0.66 – 0.96)	0.48
RA	98 ± 1.5	97 ± 1.8	-0.50	0.83	0.85 (0.53 – 0.94)	0.65

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 15: Inter-rater test for sEMG activity during the resting stage between PI and AR (TD; N = 15)

Muscle	PI / Hz	AR / Hz	Diff	SD diff	ICC (95% CI)	SEM
EO	12 ± 1.5	12 ± 2.0	0.00	0.93	0.96 (0.88 – 0.99)	0.87
IO	11 ± 1.8	10 ± 2.0	1.00	1.2	0.97 (0.91 – 0.97)	0.86
RA	10 ± 2.0	9 ± 1.5	1.00	0.8	0.95 (0.84 – 0.98)	0.87

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 16: Inter-rater test for sEMG activity during the active stage between PI and AR (TD; N = 15)

Muscle	PI / Hz	AR / Hz	Dif	SD diff	ICC (95% CI)	SEM
EO	108 ± 1.8	106 ± 2.0	2.00	1.4	0.85 (0.53 – 0.94)	0.32
IO	111 ± 2.0	112 ± 1.8	-1.00	0.9	0.89 (0.66 – 0.96)	0.39
RA	98 ± 2.0	97 ± 2.2	1.00	1.2	0.87 (0.59 – 0.95)	0.43

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 17: Inter-rater test for GMFM between PI and AR (N = 20; n = 5 in each GMFCS Level)

GMFCS Level	GMFM SCORE (%)					
	PI score ± SD	AR score ± SD	Diff (%)	SD diff	ICC (95 % CI)	SEM
I	78 ±0.68	80 ± 0.58	-2.00	0.27	0.91 (0.79 – 0.96)	0,19
II	63 ± 1.45	64 ± 1.35	-1.00	0.63	0.90 (0.78 – 0.96)	0.45
III	56.5 ± 1.05	55 ± 1.01	1.50	0.42	0.91 (0.79 – 0.96)	0.30
IV	38.4 ± 1.34	37.6 ± 1.33	0.80	0.43	0.94 (0.87 – 0.98)	0.30

PI = Measurements of Principal Investigator; AR = Measurements of Assistant Researcher

Appendix C 2: Table 18: Inter-rater test for PCI test between PI and AR (STCP: N = 15; TD: N = 15)

Group	PI score ± SD	AR score ± SD	Diff (%)	SD diff	ICC (95 % CI)	SEM
STCP	78.0 ± 1.0	76.0 ± 1.4	2.0	0.92	0.89 (0.61 – 0.96)	0.30
TD	36.0 ± 0.8	35.0 ± 1.2	1.0	0.63	0.86 (0.68 – 0.94)	0.28

PI = Principal Investigator; AR = Assistant Researcher

Appendix C 3: Direct and indirect measurement of muscle thickness

The main architectural parameter evaluated by the ultrasound machine in this study was muscle thickness. Two methods were used to measure muscle thickness. The direct method which involved a frozen electronic caliper and the indirect method involving ImageJ software.

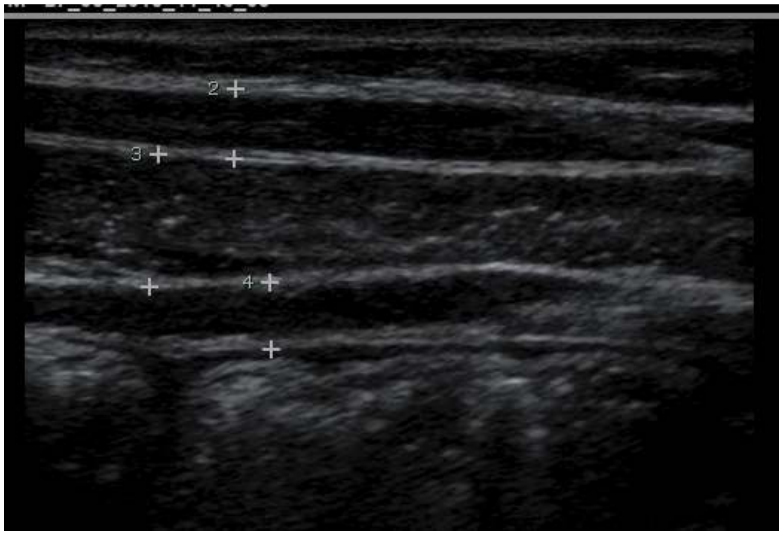
The analyses of muscle thickness in this study were all from the frozen calliper method. However, the measurement of thickness obtained by the frozen calliper method (direct) was tested against the ImageJ (indirect method). The results for muscle thickness for both methods were analysed using STATISTICA and presented below:

Appendix C 3: Table 1: Inter-rater reliability of the two methods for measuring muscle thickness using the ultrasound (Calliper /Direct method and the Pixel (Image J processor) / indirect method) for STCP (N=15)

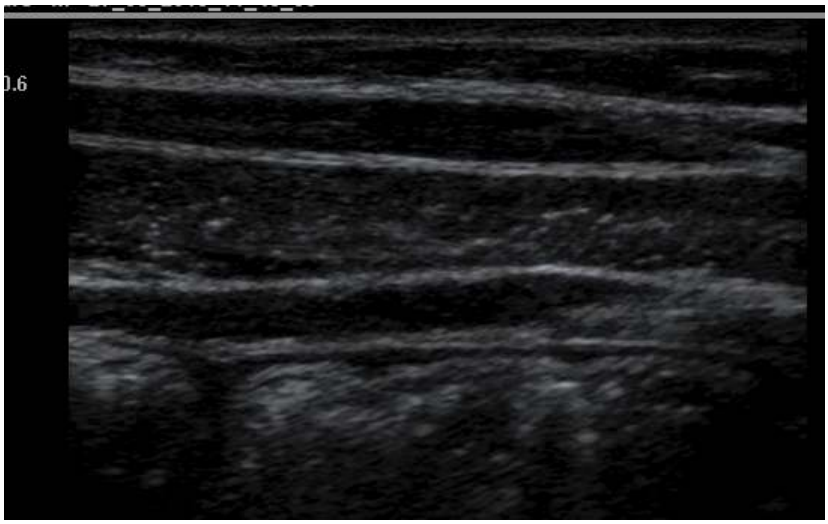
Muscle Th (mm)	Frozen Calliper Method	Pixel (Image J) method/Indirect	Diff	SD Diff	ICC (95% CI)	SEM
EO Th R	3.6 ± 0.2	3.5 ± 0.2	0.1	0.13	0.94 (0.80 – 0.98)	0.66
EO Th Ac	3.0 ± 0.4	3.0 ± 0.2	0.0	0.20	0.98 (0.92 – 0.99)	0.58
IO Th R	5.1 ± 0.4	5.0 ± 0.5	0.1	0.18	0.93 (0.78 – 0.98)	0.58
IO Th Ac	4.5 ± 0.5	4.2 ± 0.5	0.3	0.12	0.96 (0.52 -0.96)	0.51
TrA Th R	2.9 ± 0.3	3.0 ± 0.2	-0.1	0.30	0.95 (0.65 – 0.99)	0.61
TrA Th Ac	2.5 ± 0.2	2.6 ± 0.2	-0.1	0.22	0.93 (0.60 – 0.97)	0.58
RA Th R	6.2 ± 0.2	6.2 ± 0.2	0.0	0.15	0.95 (0.65 – 0.99)	0.60
RA Th Ac	6.5 ± 0.3	6.4 ± 0.5	0.1	0.14	0.93 (0.60 – 0.97)	0.56

Appendix C 3: Table 2: Inter-rater reliability of the two methods for measuring muscle thickness using the ultrasound (Calliper /Direct method and the Pixel (Image J processor) / indirect method) for TD

Muscle Th (mm)	Frozen Calliper Method	Pixel (Image J) method/Indirect	Diff	SD Diff	ICC (95% CI)	SEM
EO Th R	3.2 ± 0.2	3.4 ± 0.2	- 0.2	0.33	0.94 (0.80 – 0.98)	0.60
EO Th Ac	3.3 ± 0.4	3.5 ± 0.2	- 0.2	0.27	0.90 (0.89 – 0.99)	0.58
IO Th R	4.1 ± 0.4	4.3 ± 0.3	- 0.2	0.28	0.93 (0.78 – 0.98)	0.62
IO Th Ac	4.3 ± 0.2	4.5 ± 0.3	- 0.2	0.32	0.96 (0.52 -0.96)	0.56
TrA Th R	2.2 ± 0.3	2.0 ± 0.2	0.2	0.30	0.92 (0.55 – 0.94)	0.61
TrA Th Ac	2.5 ± 0.2	2.6 ± 0.2	-0.1	0.24	0.91 (0.60 – 0.96)	0.65
RA Th R	6.0 ± 0.2	6.0 ± 0.2	0.0	0.25	0.94 (0.85 – 0.99)	0.66
RA Th Ac	6.5 ± 0.2	6.4 ± 0.3	0.1	0.34	0.93 (0.88 – 0.97)	0. 60



Appendix C3: Figure 1: Resting stage picture showing the three anterolateral abdominal muscles with muscle thickness marked by callipers (Direct method)



Appendix C3: Figure 2: Resting stage picture showing the three anterolateral abdominal muscles ready for measurement of thickness by ImageJ (Indirect method)

Appendix C3: Figure 3: Test location in one of the schools showing the ultrasound equipment used

Appendix D: Recommendation from the doctoral degree board and the external examiners' reports

Appendix D 1: Recommendation from the doctoral degree board

Faculty of Health Sciences
Memorandum

To	Doctoral & Master's Committee (DMC)
From	Prof P Meissner – Chair: DMC
Date	13 March 2014
Subject	Matter for approval
cc	Prof G Louw; Prof M Collins

CONFIDENTIAL

Candidate:	Adjenti, Mr S
Degree:	PhD in Anatomy & Cell Biology
Department:	Human Biology
Title:	An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance
Supervisors:	Prof G Louw

RECOMMENDATIONS from External Examiners

Please find attached the reports from the three external examiners, as well as an abstract.

- The first examiner (Bosman) recommended that the degree be awarded without any corrections being made to the thesis with the exception of minor typographical errors;
- The second examiner (D'Antoni) recommended that the degree be awarded without any corrections being made to the thesis with the exception of minor typographical errors;
- The third examiner (Tubbs) recommended that the degree be awarded subject to a number of specified changes being made to the thesis to the satisfaction of the DDB.

Recommendation:

1. that the candidate be awarded the degree subject to a number of specified changes being made to the thesis to the satisfaction of the DDB;
2. that **Prof G Louw** be requested to oversee these changes and certify his satisfaction on completion of these corrections.

If you have any objection to these recommendations, please contact Adri Winckler by phone at: Tel 406 6327 or by email at: Adri.Winckler@uct.ac.za by **no later than 15:00 on Tuesday, 18 March 2014**

Prof P N Meissner
Chair: DMC

Appedix D 2: Report of external examiner 1

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Attn: Mrs Janine Isaacs

The Doctoral Degrees Board Officer
University of Cape Town
Private Bag X3
RONDEBOSCH
7701

Dear Mrs Isaacs

EXTERNAL EXAMINER'S REPORT: PROF MC BOSMAN

Examination of PhD thesis of Mr S Adjenti (ADJSAV001) with the title: An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural performance

Expectations of the candidate

The candidate most convincingly explained the relevancy and purpose of the research project. The treatment of patients suffering from cerebral palsy, particularly the spastic type, is of great importance to help them attain a better quality of life. The question whether the anterior abdominal muscles exert a positive action in preventing anterior pelvic tilt and thereby limiting excessive lumbar lordosis, with concomitant lower back pain, is very relevant. Any information that may aid therapists to improve the treatment of patients with this deficiency can only be lauded.

The candidate demonstrated an extensive and current knowledge regarding the available literature on all aspects of the subject. He cited relevant findings of other studies and dealt appropriately with the various physiological processes and morphological changes involved in the muscles concerned. He also succeeded in relating this to the clinical implications – and possible application – thereof.

The candidate clearly mastered the techniques and methods required in this investigation. His background in anatomy and, no doubt, the clinical expertise of the co-supervisors stood him in good stead in this regard and he also succeeded most admirably in presenting the relevant statistics in a clear and useful manner.

The results are clearly illustrated with tables and figures. This is augmented with exceptional statistical evaluations, which leaves no room for doubt whatsoever about the findings. All of the above permits easy and understandable visualisation of the results.

The discussion and conclusion chapters provide abundant proof that the candidate is more than capable of evaluating the scientific importance and validity of his findings. He also displays an extraordinary ability to interpret his results and extrapolate its relevance in clinical practice.

Assessment of the dissertation:

The thesis complies with the requirements for the degree of PhD. The information it contains is particularly valuable to medical science and the treatment of cerebral palsy patients in general –

Department of Anatomy
School of Medicine
Faculty of Health Sciences
University of Pretoria
Private Bag x323
ARCADIA 0007
Republic of South Africa

Tel +27 12 319 2233
Fax +27 12 319 2240

marius.bosman@up.ac.za
http://www.up.ac.za

especially clinicians in the physiotherapy and occupational therapy disciplines – since it contains essential information on the changes and actions of the anterior abdominal muscles, particularly with regard to patients suffering from the spastic type of paralysis. This should aid practitioners in designing a more holistic treatment of their patients and help to strengthen their musculature to ameliorate their condition.

Recommendation:

This is an outstanding endeavour, which is exceptionally well-written and I recommend that it be accepted with the proviso that the candidate affects the minor corrections suggested. I note that the original title of the project differs from the current one and must assume that this was amended through the correct channels. It is definitely not necessary to submit the thesis for re-examination.

Although doctoral degrees in the RSA are not graded, I nevertheless believe that this work is worthy of a distinction and the candidate can be commended for his effort and diligence. The hope is expressed that the candidate will continue with the research in this field and also publish his results as prominently as possible.

Sincerely

Prof MC Bosman
Head: Department of Anatomy
Head: Section of Clinical Anatomy

Appendix D 3: Report of external examiner 2

EXAMINER'S RECOMMENDATION FORM

RECOMMENDATION ON EXAMINATION OF PhD THESIS SUBMITTED BY
UNIVERSITY OF CAPE TOWN CANDIDATE

STRICTLY CONFIDENTIAL

To: THE DOCTORAL DEGREES BOARD
University of Cape Town
Private Bag, Rondebosch
7701 South Africa

FROM Dr. A D'Antoni
50 PLEASANT STREET
STATEN ISLAND
NEW YORK, 10308
USA

PhD CANDIDATE: Mr S Adjenti ADJSAV001

THESIS TITLE: An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance

I have examined this thesis and recommend (please tick the appropriate box) that:

a) the candidate should be awarded the degree and no corrections need be made to the thesis, with the exception of minor typographical errors only. ☑

b) the candidate should be awarded the degree subject to specified changes being made to the thesis to the satisfaction of the Doctoral Degrees Board. ☐

c) although the thesis does not meet the required standard, the candidate should be invited to do further work as necessary and to revise and resubmit for re-examination. ☐

d) the degree should not be awarded to the candidate ☐

I AGREE TO DISCLOSURE OF MY NAME TO THE CANDIDATE ☑

I OBJECT TO DISCLOSURE OF MY NAME TO THE CANDIDATE ☐

I ENCLOSE A REPORT ON THE THESIS

SIGNED: ....

DATE: 2-10-2014

Anthony V. D'Antoni, DC, PhD
adantoni@nycpm.edu

Title: An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance

Author: Saviour Adjenti (ADJSAV001)

OVERALL IMPRESSION

This is a solid doctoral dissertation that demonstrates great effort on the part of Mr. Adjenti and it was a pleasure to read. The dissertation committee should be commended for supervising this student and allowing a topic that has both anatomic and clinical relevance to come to fruition. The experiment of which this dissertation is based is clearly rooted in the scientific method and the theoretical framework of the study is sound. Mr. Adjenti performed a robust review of the available literature related to the topic. The inclusion and exclusion criteria were described in great detail as was the method used to calculate the sample size (*N*). The rationale for each statistical test was justified. Permission to conduct this study was granted by an ethical review board and informed consent was obtained. I believe that this study will satisfactorily undergo peer review and eventually be published in a scientific journal. Many of comments below should help Mr. Adjenti as he transforms this dissertation into a manuscript suitable for publication in a peer-reviewed journal. None of these comments are obligatory except for minor typographical/grammatical errors that I found. Kindly see the Examiner's Recommendation Form for my final recommendation.

Appendix D 4: Report of external examiner 3

EXAMINER'S RECOMMENDATION FORM

RECOMMENDATION ON EXAMINATION OF PhD THESIS SUBMITTED BY
UNIVERSITY OF CAPE TOWN CANDIDATE

STRICTLY CONFIDENTIAL

To: THE DOCTORAL DEGREES BOARD
University of Cape Town
Private Bag, Rondebosch
7701 South Africa

FROM Dr. S Tubbs
Pediatric Neurosurgery
Lowder 400
Children's of Alabama
1600 7th Avenue South
Birmingham, Alabama 35233
USA

PhD CANDIDATE: Mr S Adjenti ADJSAV001

THESIS TITLE An investigation into the ultrastructural parameters of abdominal muscles in children and adolescents with spastic type cerebral palsy and the effect on postural muscle performance

I have examined this thesis and recommend (please tick the appropriate box) that:

a) the candidate should be awarded the degree and no corrections need be made to the thesis, with the exception of minor typographical errors only. ☐

b) the candidate should be awarded the degree subject to specified changes being made to the thesis to the satisfaction of the Doctoral Degrees Board. ☑

c) although the thesis does not meet the required standard, the candidate should be invited to do further work as necessary and to revise and resubmit for re-examination. ☐

d) the degree should not be awarded to the candidate ☐

I AGREE TO DISCLOSURE OF MY NAME TO THE CANDIDATE ☑

I OBJECT TO DISCLOSURE OF MY NAME TO THE CANDIDATE ☐

I ENCLOSE A REPORT ON THE THESIS

I appreciate the work that you have done for your study. This certainly addresses an area that has not been investigated well. Please find below my minor edits that will improve the overall presentation of your document.

You should mention that there is a potential for misdiagnosis of CP, especially since none of the children in your study underwent imaging of the craniospinal axis.

Exclusion criteria should include dorsal rhizotomy and baclofen pump placement

Page iii Dr Asfree should be Dr. Asfree

Page v change "is acquired at" to "usually occurs"

Page v "TD" should be defined before using the abbreviation on this page.

Has Noraxan been validated with other studies?

Page vi need "," after "(GMFM)" and "However"

Page 1 "prevalence" should be "incidence"

Page 1, 1st paragraph, lines 11-12 "cerebral palsy" should be "CP"

Page 1, 2nd paragraph, line 1, need "," after "muscles"

Page 3, 2nd paragraph, line 8 need "," after "CP".

Page 4, 2nd paragraph, sentence #1, add "degree of" prior to "lumbar lordosis"

Page 8 don't capitalize Ultrasonography and Physiological Cost Index should be PCI

Page 9, add "on ultrasound" after "structure" under Aims of study. Also, need comma after "ultrasonography" on 3rd line of the Aims of study. Instead of mentioning the need of commas throughout the remainder of the paper, I will simply alert you as to the need for editing in this regard in several places in the document.

Page 13, on the second paragraph, you use STCP on line 2 but then define it on line 4.

Page 13, Cerebral palsy should be cerebral palsy.

Page 16, 2nd paragraph, line 5 "plenty of" should be reworded.

Page 16, last line, a space is needed before "muscles"