THE DEVELOPMENT AND VALIDATION OF A MOVEMENT EVALUATION SYSTEM FOR CHILDREN WITH CEREBRAL PALSY

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THE DEVELOPMENT AND VALIDATION OF A MOVEMENT EVALUATION SYSTEM FOR CHILDREN WITH CEREBRAL PALSY

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Para papá, que con su esfuerzo y dedicación me guio en este viaje,

aunque se haya ido antes de verme llegar a puerto.

Para mamá, que con su amor, valor y generosidad me mantuvo a flote,

aún en las noches de tormenta.

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List of Abbreviations

.CMO	C-Motion Output
.csv	Comma Separated Values
.mat	Matfile
.wmv	Windows Media Video
°	Degrees
2D	Bi-dimentional
3D	Three-dimensional
6DoF	Six Degrees of Freedom
A	Absolute angles
AA	Aligned Angles
AD-Group	Adult group
AIMS	Alberta Infant Motor Scale
ASIS	Anterior Superior Iliac Spine
$A\alpha_S$	Absolute Segmental Angles
C7	7th cervical vertebra
CE	Conductive Education
CH-Group	Children group
CIMT	Constraint Induce Movement Therapy
Closed-CKC	Closed Controlled Kinetic Chain
CNS	Central Nervous System
COP	Centre of Pressure
CP	Cerebral Palsy
D	Detrended angles
$DA\alpha_S$	Dartfish Absolute Segmental Angles

DF-operator	Dartfish operator
EBP	Evidence Based Practice
EMG	Electromyography
FS	Free Sitting
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
Hz	Hertz
ICC	Intra Class Correlation
IR	Infrared
L5	5^{th} lumbar vertebra
LL	Lower-Lumbar
LT	Lower-Thoracic
m	Meters
M+SD	Mean Absolute Deviation plus SD
MATLAB	Matrix Laboratory
MAX	Absolute Maximum Deviation
ME	Mean Error
mm	Millimetres
MT	Mid-Thoracic
NDT	Neurodevelopmental Therapy
NIHPE	Non-invasive human pose estimation
Open-CKC	Open Controlled Kinetic Chain
PEDI	Pediatric Evaluation of Disability Inventory
RGB-D	Red, Green, Blue -Depth
RMSE	Root Mean Square Error
SACND	Sitting Assessment for Children with Neuromotor Dysfunction

SATCo	Segmental Assessment of Trunk Control
SD	Standard Deviation
SDK	Software Development Kit
T12	12th thoracic vertebra
TCMS	Trunk Control Measurement Scale
THR	Therapeutic Horseback Riding
TT	Targeted Training
UL	Upper-Lumbar
UT	Upper-Thoracic
V3D	Visual3D
VAα_s	Vicon Absolute Segmental Angles
VR	Virtual Reality
α_s	Segmental angles

Dissemination of Study Findings

1. Published Articles

- María B. Sánchez, Ian Loram, Paul Holmes, John Darby and Penelope B. Butler. (2017). A video based method to quantify posture of the head and trunk in sitting. *Gait & Posture, 51,* 181-187.

- María B. Sánchez, Ian Loram, Paul Holmes, John Darby and Penelope B. Butler. (2017). The potential of an automated system to identify the upper limb component of a controlled sitting posture. *Gait & Posture, 58,* 223-228.

2. Conference Presentations

- María B. Sánchez, Ian Loram, Paul Holmes, John Darby and Penelope B. Butler (2016). Quantification of Head Movement When Testing Segmental Trunk Control. Robert Jones & Agnes Hunt Hospital (RJAH) Research Day, Oswestry –UK. [Podium Presentation]

3. Published Abstracts

- María B. Sánchez, Ian Loram, John Darby, Paul Holmes and Penelope B. Butler (2016). Posture of the Head and Trunk in Sitting: Quantification Of Alignment. Published in: XXI International Society of Electrophysiology and Kinesiology (ISEK) Congress. P2-I-62. [Poster presentation].

- María B. Sánchez, Ian Loram, John Darby, Paul Holmes and Penelope B. Butler (2016). Posture of the Head and Trunk in Sitting: Quantification of Head Movement When Testing Segmental Trunk Control. Published in:

XXI International Society of Electrophysiology and Kinesiology (ISEK) Congress. P3-E-65. [Poster presentation].

- María B. Sánchez, Ian Loram, Paul Holmes, John Darby and Penelope B. Butler (2014). Development and Validation of a Movement Evaluation System: Trunk Alignment. *Proceedings of The 7th MMU Postgraduate Research Conference 2014*, pp 53. [Poster presentation].

4. Other Associated Publications

- John Darby, María B. Sánchez, Penelope B. Butler, Ian D. Loram. (2016) An evaluation of 3D head pose estimation using the Microsoft Kinect v2. *Gait & Posture*, 48,83-88.

Reference style used in the present thesis follows the reference guidelines of Gait & Posture.

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Preface

This thesis is focused on the development of a method for the objective assessment of head and trunk postural control in sitting. The work has six main sections: Introduction, Literature Review, Objective, Methods, Studies, and Discussion and Future Work.

The **Introduction** presents the background and context of this project, noting that the creation of an objective tool for the assessment of head and trunk control is an important contribution to the validation of physiotherapeutic interventions used in a routine clinical practice. It also describes how objective measures have great potential for the assessment of patients with neuromotor disabilities and especially for the assessment of control of children with cerebral palsy (CP). The Introduction gives the overall aim of the project.

The **Literature Review** is subdivided into each of the main concepts that support this thesis: Cerebral Palsy, Targeted Training, Postural Alignment Assessment Methods and Controlled Kinetic Chains. The Cerebral Palsy chapter describes the general characteristics of the condition as well as the specific importance of head and trunk control to the acquisition and maintenance of an independent aligned posture. The chapter on Targeted Training and other therapeutic interventions includes a general overview of different approaches commonly used in physiotherapy treatment for children with CP; a summary of the evidence of their effectiveness is also included. The chapter reviewing Methods Assessment of Postural Alignment reports the various methods currently used to quantify posture, their potential for use in a routine clinical context and their applicability for patients of wide age range and differing pathologies. In the final chapter of this section, Controlled Kinetic Chains, the concept of the Controlled Kinetic Chain (CKC) is described in detail and the vital role this concept plays in the demonstration of trunk control.

The Introduction and the ‘current state of the art’ gained from the Literature Review enabled the formulation of the specific **Objective** “to develop a clinical tool for the objective measurement of head and trunk postural control in sitting for children with cerebral palsy”. Three main components were defined to meet the aim of this project: i) quantification of alignment, ii) identification of the upper limb position as an essential component of a CKC, and iii) their combination to develop a quantitative measure of static segmental trunk control. These components are mirrored in the Studies, as described below.

The **Methods** section describes the two main methods used for data collection in this project: three-dimensional (3D) motion capture system and analysis (Vicon and Visual3D), and video (processed using Dartfish). This Chapter also includes a detailed description of the processing and analysis performed in MATLAB for each study.

The **Studies** section has three main chapters, which reflect the main components required to meet the Objective. The ‘Quantification of Seated Postural Alignment of the Head and Trunk’ generated a method to quantify the head and trunk posture in sitting of a group of healthy adults; this study presents the validation of video analysis as used in this work against the gold standard for movement analysis. The ‘Objective Identification of the Upper Limb Component of a Controlled Sitting Posture’ validated the use of a 3D motion capture system in the positive identification of Open Controlled Kinetic Chains (Open-CKC) and validated the clinical identification of Open-CKC from both frontal and oblique video recordings in a group of adults and a group of children with CP. The final study, ‘Quantitative Classification of the Segmental Level of Head and Trunk Control in Children with Cerebral Palsy’, takes the findings from the two previous studies and combines them to create a quantitative measurement of segmental trunk control; it compares the objective and clinical judgement of the segmental level of trunk control of a group of children with CP.

The thesis concludes with the general **Discussion and Future Work.** This summarises the main findings of the studies described above, and indicates how the information that has been generated from the present work is fundamental for the development of fully automated objective tools for the assessment of control and appropriate for use in physiotherapy clinics. This, in turn, links back to means of validating specific therapeutic interventions identified in the Introduction.

The **Appendix** section includes a detailed description of the Segmental Assessment of Trunk Control (SATCo) as a fundamental basis to this work. There is also an Appendix that reports the findings of a complementary study looking at other aspects of postural control additional to the static posture (SAR Analysis). Finally, there are copies of the manuscripts accepted/submitted for publication at the time of printing of this thesis.

A summary diagram of this thesis is presented in Figure 0-1.

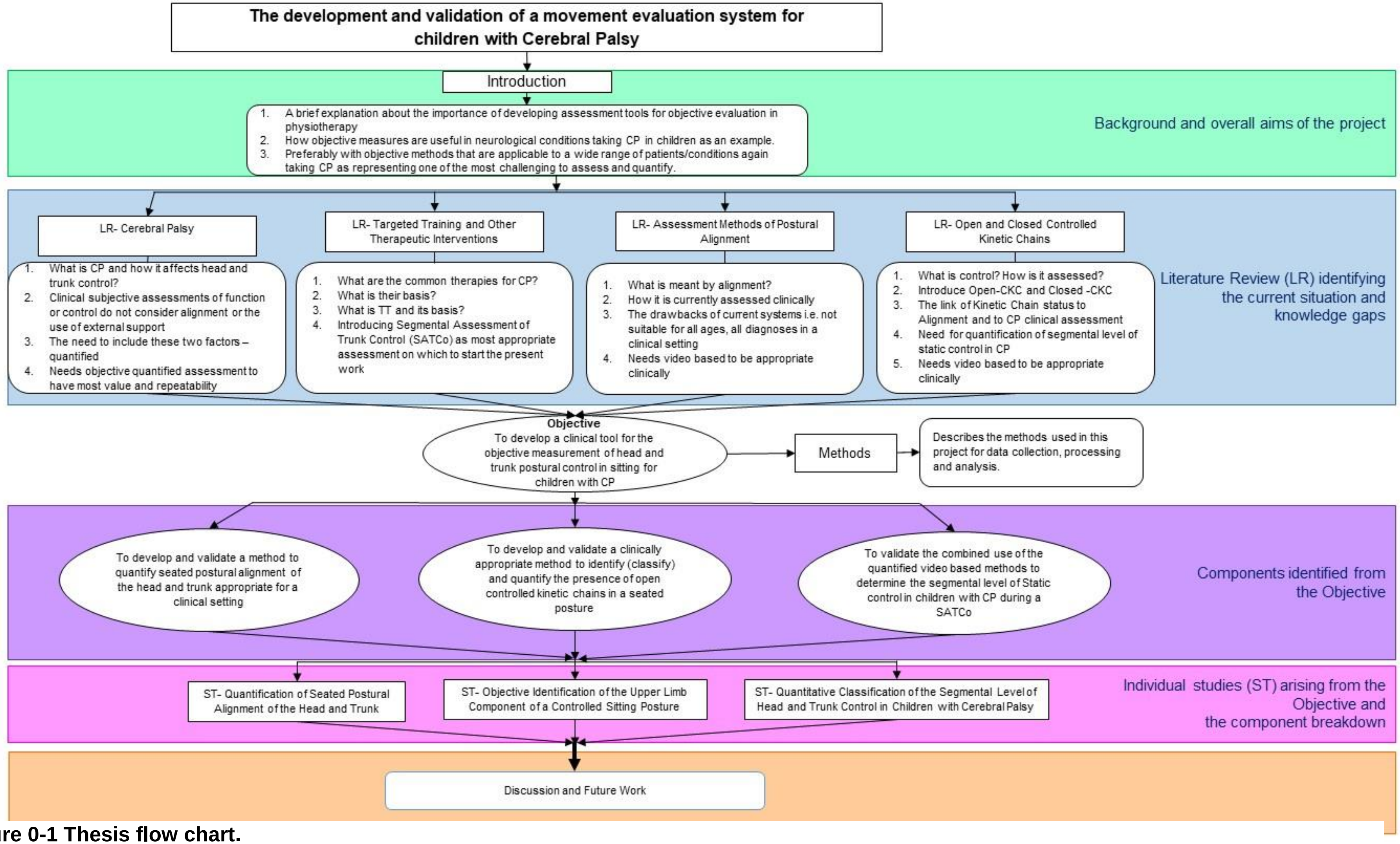

Figure 0-1 Thesis flow chart.

Thesis Abstract

The development of objective assessment tools for evaluation in physiotherapy is vital. Currently, the outcomes resulting from an intervention are generated by clinical assessments that are almost exclusively based on subjective criteria which rely upon the assessor's expertise and consistency. The aim of this project was to develop an objective clinical tool to measure head and trunk postural control in sitting for children with cerebral palsy (CP). It is preferable for any objective measurement tool to be useable with as wide a range of patients and conditions as possible. Ideally, the tool should also be 'clinically-friendly' for both therapist and patient. This project took children with CP as a starting point, as representing one of the most challenging groups to assess and to quantify. The project was specifically focused on head-trunk control in sitting because of the importance of this posture for activities of daily living.

The Literature Reviews confirmed that head-trunk control status in sitting could be defined by an aligned sitting posture without any external support for the head, trunk and upper limbs. The Method selected was video-based (Dartfish) to meet the requirement of 'clinically-friendly' and developed to quantify alignment (and deviations from alignment) of the head and trunk with small errors when compared to a 3D motion capture system (Vicon). The Dartfish method was also used to classify the positions of the upper limbs in comparison with the standard clinical classification; it showed that a simplified representation of the hands and elbows can reflect the clinical judgement. The combination of both these elements enabled the quantification of head/trunk control in children with CP for the first time.

The work presented in this thesis makes a new and major contribution to postural assessment. It also provides the basis for the development of a fully automated system for the objective assessment of control using 2D-video recording. This work confirmed that clinical assessments can be objectively replicated, representing a major advance in the validation of physiotherapy interventions.

Introduction

I. Introduction and Aims

In physiotherapy, it is common to amend and change a therapeutic intervention as a treatment plan progresses. Changes can be the result of, for example, the achievement of the defined therapeutic goals. In routine physiotherapy clinics, therapists would usually make the adjustments to the therapeutic plans based on the theory that supports the therapeutic intervention implemented and their own professional experience. This process, although practical, is not always supported by evidence, and it does not then follow the requirements of evidence-based practice (EBP). EBP integrates the best research evidence, individual clinical expertise and patient choice in making decisions about the care of patients [2]. EBP is desirable as it helps to standardise intervention protocols and provides validated support to the decision making. In the process of validating a therapeutic intervention, it is fundamental to have well defined assessments that accurately reflect the main object of the therapy; for example, if the main objective of a therapeutic plan is to restore the complete mobility of a joint after an injury, the evaluation to assess the initial condition and the progress with therapy should be a range of motion measurement.

However, the traditional and commonly used assessments tend to be based on a subjective evaluation. Subjective assessments provide a qualitative judgement that has the limitation of depending upon the assessor's expertise. Thus, the definition of the baseline at the beginning of an intervention, and the identification of changes would potentially be based on the ability of the assessor to maintain reliable criteria, or on the homogeneity of the group of assessors working at the same clinic. This can further confound the process of validating a therapeutic intervention. This process, however, could be complemented by the use of objective measurement tools. An objective measurement tool provides a quantitative measure that represents the status of a patient at a given time;

furthermore, with an objective measure the results obtained at different time points would reflect the real change of the patient that might result from a specific therapeutic intervention rather than any change in assessor criteria.

Ideally an objective measurement tool should be ‘clinically-friendly’, both for therapists and for patients, and minimally disruptive to the normal physiotherapy assessment. Furthermore, the objective assessment system should not require complex or expensive equipment, as it will reduce the opportunity for use in a regular physiotherapy clinic. Ideally, a robust clinical outcome measurement tool should have the potential to be applicable to more than one group of patients; this would make the tool more cost-effective and widely used. Although the result from an objective measurement tool is a quantitative representation of a clinical outcome, it is important to consider how the quantitative result reflects the traditional subjective clinical concept, and how accurately both reflect the object of the therapeutic intervention.

Objective measurement tools could thus have a major positive impact in many different areas of physiotherapy. For example, in the assessment of patients with neuromotor disorders, a physiotherapist normally uses observation as the main assessment tool. Neuromotor disorders compromise an adult or child’s ability to move, as a consequence of the neurological damage [3]; a clear understanding of the extent of the motor disability is therefore fundamental to the development of a customised therapeutic plan. To gain this understanding and formulate a treatment plan through observation alone is challenging, even if the observer is skilled. It also does not readily comply with the requirement for EBP. Neuromotor disorders encompass many different conditions including stroke and Parkinson’s disease in adults, and cerebral palsy (CP) in children. In this project the focus was on CP because it is the most common motor disability in childhood [4] with consequences persisting through the lifespan [5]. Furthermore, children with CP represent one of the most challenging groups to assess and for quantification of that assessment, thus, any positive outcome of research on topics related to CP has a large impact potential worldwide. This is especially true if the research aims to validate therapeutic interventions.

In CP, the motor compromise that results from the brain injury often results in functional limitations, especially when there is head and trunk involvement.

Functional limitations might prevent the child performing activities of daily living, or taking part in social activities [6]. Physiotherapy is then an essential component in the management of a child with CP. In routine physiotherapy clinics, different therapeutic approaches are used that aim at improving the child's function and many of these are in regular use worldwide. However, recent reviews [7-9] have found that, overall, there is only weak general evidence of the real impact of these therapies in improving motor control and/or function; furthermore, there is no clear understanding of the underlying mechanisms of how these therapies address and improve head and trunk control. However, at present, these therapies are a fundamental part of the overall therapeutic plan defined for each child to achieve the specified functional goals. There is a clear need for the use of therapy approaches that are supported by robust evidence using a reliable assessment method. Only then can the value of one therapeutic approach over another be clearly established. The development of an objective method to measure motor control is the primary starting point since functional skills are reliant upon control status.

The main Objective of this project was to develop a clinical tool for the objective measurement of head and trunk postural control in sitting for children with cerebral palsy. Sitting is a basic and common posture that is a fundamental of physiotherapy for individuals with neurodisability as sitting allows the execution of many functional skills. Developing a method to assess postural control in sitting could thus offer a well-defined framework for the future development of objective measurement tools in physiotherapy.

Literature Review

II. Cerebral Palsy

1. Introduction

Have you ever thought about how you would cope if you were not able to move as you do or to have the neuromuscular control that you have? Suppose you were not able to hold yourself up to look around? How difficult would it be to read these lines if your head was so unstable that you were constantly looking first at the ceiling and then at the floor?

Humans develop along a certain path, starting their life as dependent babies to grow into independent adults who can walk around the world, communicate and interact with each other. However, for some children, this is not the developmental path that is followed. An alteration in the usual developmental sequence can be the result of a genetic abnormality, or an injury to the immature brain. Such brain damage, which can occur before, during, or after birth within the first two or three years of life from a variety of causes, will frequently compromise the ability to control body movement. In turn, this will adversely impact the ability to perform ordinary functional activities such as holding the head still while holding a book and reading. This brain damage and its sequelae is commonly known as ‘cerebral palsy’.

This chapter will focus on the definition of ‘cerebral palsy’, its incidence and classification, and the implications of the brain injury on movement and control of movement. An overview of the common clinical assessments of function and motor control will be presented; emphasis will be made on the importance of assessing all the elements of control, focusing particularly on the control of the head and trunk. These elements are the basis of the work presented in this thesis and will help to illustrate the importance of the work developed in the present PhD.

2. Definition

The term ‘cerebral palsy’ (CP) is commonly used to refer to a “neurodevelopmental condition beginning in early childhood and persisting through the lifespan” [5]. The most common description is that CP is an ‘umbrella term’ used for a group of disorders characterised by motor dysfunction due to non-progressive brain damage early in life [5, 10, 11]. Although there are clear criteria to identify the CP condition, until recent years there has been no exact definition of the term. As a consequence, classification of the type and characteristics of the sub-categories of CP tended to be variable.

However, ‘The Definition and Classification of Cerebral Palsy, April 2006’ [5] encompasses the heterogeneity of the disorders covered by the term, as well as the characteristics of age presentation and the non-progressive nature of the brain injury. The definition reads as follows:

“Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication, and behaviour, by epilepsy, and by secondary musculoskeletal problems.” (pg. 9)

This definition clarifies the need for the physiotherapist to fully recognise the consequences and challenges a child might face in his or her everyday life in order to deliver effective treatment. Although the brain lesion is non-progressive, the secondary musculoskeletal problems in particular do become more problematic as the child grows. For example, muscle length may not increase with bone length, leading to increasing muscle contracture and joints that therefore become more limited in their range of motion. This inevitably has an adverse impact on functional activity and this effect can be seen in some children as early as 12 months of age [10]. However, the magnitude of this impact on functional activity is also associated with the type and characteristics of CP as discussed in the next section.

3. Incidence, Pathology and Classification

Cerebral palsy is the most common motor disability of childhood affecting 1.5 to 4 per 1000 live births worldwide [4]. In the United Kingdom, around 2000 babies are diagnosed with CP every year, or one in every 400 children [12, 13]. CP is usually diagnosed during the child's first three years of life; however, they will experience lifelong motor difficulties. The severity of these difficulties varies greatly in relation to the site and extent of the brain injury, which will also determine the involvement of the limbs and body.

CP is the result of multifactorial causes with an end result of hypoxic damage to the nerve cells [14]. The main causes for the hypoxic damage are white-matter damage of immaturity (periventricular leukomalacia and periventricular haemorrhage), basal ganglia lesions, cortical and subcortical lesions, and focal infarcts (Table II-1) [14, 15]. These causes are closely related to the CP typical classification by the distribution of the movement disorder and by the type. The most common topographical classifications are: hemiplegia, where the limbs and body on one side are primarily affected; diplegia, where the involvement of the legs is greater than of the arms; and quadriplegia (also known as total body involvement), where the body and all four limbs are affected (Table II-) [10, 14, 15]. The 'Surveillance of Cerebral Palsy in Europe' divides CP into three groups based on the predominant neuromotor abnormality: spastic (84%[1]), dyskinetic (12%) or ataxic (4%), with dyskinesia further differentiated into dystonia and choreoathetosis [10, 14, 16]. The combination of the topographic distribution and the type of CP will determine the degree of motor impairment, which will, in time, define the degree of functional limitation and participation.

Children with hemiplegic and diplegic CP are generally able to sit and to walk functionally; in contrast, only one third of children with quadriplegic CP attain functional sitting and less than a tenth achieve walking (Table II-1). Children with hemiplegic CP tend to have mild functional severity; while children with diplegic CP generally have moderate functional constraints. In contrast, more than two thirds of children with quadriplegic CP are severely functionally impaired (Table

[1] Bax et al. [14].consider that the classification by distribution only applies for the spastic type and present the spastic percentages as separated values. Here these values have been added to present a single value that represents the percentage of incidence of spastic CP.

II-1) [15]. Comprehensive assessment of the musculoskeletal and functional limitations is therefore fundamental to determine the type and extent of external support a child needs to perform daily activities.

This is reflected in the Gross Motor Function Classification System (GMFCS) [17]. The GMFCS provides a means to define the degree to which CP is impacting the child and gives an indication of prognosis (Table II-2). This classification gives five ordinal levels of severity of movement disability, ranging from children who can perform all the activities of their age-matched peers, even if with some difficulty of speed, balance and coordination (GMFCS Level I) to those children with difficulty controlling their head and trunk posture in most positions and in achieving any voluntary control of movement (GMFCS Level V). An understanding of how the motor control impairment limits a child's function is thus essential for accurate intervention to improve function and to avoid further musculoskeletal complications.

Table II-1 Incidence, pathology and classification of cerebral palsy.

+ The percentage values presented for the distribution were calculated from Table 2 in Bax et al. [14]. The percentage per classification was calculated as % = n*100/N, where 'n' is the number of cases reported in the table and 'N' is the added value of all the 'n'.

Movement disorder	Incidence+	Cause	Functional Compromise			Functional Ability	
			Mild	Moderate	Severe	To sit	To walk
Hemiplegia	33%	Focal infarct (contralateral to the most affected hemibody) Periventricular leukomalacia	63%	34%	3%	100%	89%
Diplegia	43%	Periventricular leukomalacia Periventricular haemorrhage	34%	46%	20%	85%	63%
Quadriplegia	24%	Cortical – subcortical lesions	7%	14%	79%	35%	9%

Table II-2 Gross Motor Function Classification System (GMFCS)[2].

LEVEL	Before 2nd Birthday	Between 2nd and 4th Birthday
I	Infants move in and out of sitting and floor sit with both hands free to manipulate objects. Infants crawl on hands and knees, pull to stand and take steps holding on to furniture. Infants walk between 18 months and 2 years of age without the need for any assistive mobility device.	Children floor sit with both hands free to manipulate objects. Movements in and out of floor sitting and standing are performed without adult assistance. Children walk as the preferred method of mobility without the need for any assistive mobility device.
II	Infants maintain floor sitting but may need to use their hands for support to maintain balance. Infants creep on their stomach or crawl on hands and knees. Infants may pull to stand and take steps holding on to furniture.	Children floor sit but may have difficulty with balance when both hands are free to manipulate objects. Movements in and out of sitting are performed without adult assistance. Children pull to stand on a stable surface. Children crawl on hands and knees with a reciprocal pattern, cruise holding onto furniture and walk using an assistive mobility device as preferred methods of mobility
III	Infants maintain floor sitting when the low back is supported. Infants roll and creep forward on their stomachs.	Children maintain floor sitting often by "W-sitting" (sitting between flexed and internally rotated hips and knees) and may require adult assistance to assume sitting. Children creep on their stomach or crawl on hands and knees (often without reciprocal leg movements) as their primary methods of self-mobility. Children may pull to stand on a stable surface and cruise short distances. Children may walk short distances indoors using a hand-held mobility device (walker) and adult assistance for steering and turning
IV	Infants have head control but trunk support is required for floor sitting. Infants can roll to supine and may roll to prone.	Children floor sit when placed, but are unable to maintain alignment and balance without use of their hands for support. Children frequently require adaptive equipment for sitting and standing. Self-mobility for short distances (within a room) is achieved through rolling, creeping on stomach, or crawling on hands and knees without reciprocal leg movement.
V	Physical impairments limit voluntary control of movement. Infants are unable to maintain antigravity head and trunk postures in prone and sitting. Infants require adult assistance to roll.	Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent movement and are transported. Some children achieve self-mobility using a powered wheelchair with extensive adaptations.

[2] Taken from Russell et al. [18].

Table II-2 Gross Motor Function Classification System (GMFCS) (continuation).

LEVEL	Between 4th and 6th Birthday
I	Children get into and out of, and sit in, a chair without the need for hand support. Children move from the floor and from chair sitting to standing without the need for objects for support. Children walk indoors and outdoors, and climb stairs. Emerging ability to run and jump.
II	Children sit in a chair with both hands free to manipulate objects. Children move from the floor to standing and from chair sitting to standing but often require a stable surface to push or pull up on with their arms. Children walk without the need for a handheld mobility device indoors and for short distances on level surfaces outdoors. Children climb stairs holding onto a railing but are unable to run or jump.
III	Children sit on a regular chair but may require pelvic or trunk support to maximize hand function. Children move in and out of chair sitting using a stable surface to push on or pull up with their arms. Children walk with a hand-held mobility device on level surfaces and climb stairs with assistance from an adult. Children frequently are transported when traveling for long distances or outdoors on uneven terrain.
IV	Children sit on a chair but need adaptive seating for trunk control and to maximize hand function. Children move in and out of chair sitting with assistance from an adult or a stable surface to push or pull up on with their arms. Children may at best walk short distances with a walker and adult supervision but have difficulty turning and maintaining balance on uneven surfaces. Children are transported in the community. Children may achieve self-mobility using a powered wheelchair.
V	Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent movement and are transported. Some children achieve self-mobility using a powered wheelchair with extensive adaptations.

Table II-2 Gross Motor Function Classification System (GMFCS) (continuation).

LEVEL	Between 6th and 12th Birthday
I	Children walk at home, school, outdoors, and in the community. Children are able to walk up and down curbs without physical assistance and stairs without the use of a railing. Children perform gross motor skills such as running and jumping but speed, balance, and coordination are limited. Children may participate in physical activities and sports depending on personal choices and environmental factors.
II	Children walk in most settings. Children may experience difficulty walking long distances and balancing on uneven terrain, inclines, in crowded areas, confined spaces or when carrying objects. Children walk up and down stairs holding onto a railing or with physical assistance if there is no railing. Outdoors and in the community, children may walk with physical assistance, a hand-held mobility device, or use wheeled mobility when traveling long distances. Children have at best only minimal ability to perform gross motor skills such as running and jumping. Limitations in performance of gross motor skills may necessitate adaptations to enable participation in physical activities and sports.
III	Children walk using a hand-held mobility device in most indoor settings. When seated, children may require a seat belt for pelvic alignment and balance. Sit-to-stand and floor-to-stand transfers require physical assistance of a person or support surface. When traveling long distances, children use some form of wheeled mobility. Children may walk up and down stairs holding onto a railing with supervision or physical assistance. Limitations in walking may necessitate adaptations to enable participation in physical activities and sports including self-propelling a manual wheelchair or powered mobility.
IV	Children use methods of mobility that require physical assistance or powered mobility in most settings. Children require adaptive seating for trunk and pelvic control and physical assistance for most transfers. At home, children use floor mobility (roll, creep, or crawl), walk short distances with physical assistance, or use powered mobility. When positioned, children may use a body support walker at home or school. At school, outdoors, and in the community, children are transported in a manual wheelchair or use powered mobility. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports, including physical assistance and/or powered mobility
V	Children are transported in a manual wheelchair in all settings. Children are limited in their ability to maintain antigravity head and trunk postures and control arm and leg movements. Assistive technology is used to improve head alignment, seating, standing, and and/or mobility but limitations are not fully compensated by equipment. Transfers require complete physical assistance of an adult. At home, children may move short distances on the floor or may be carried by an adult. Children may achieve selfmobility using powered mobility with extensive adaptations for seating and control access. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports including physical assistance and using powered mobility

4. Motor Control, Definition and Assessment

Motor control, as defined by Shumway-Cook and Woollacott [19], is “the ability to regulate or direct the mechanisms essential to movement”. This implies that motor control reflects the competence of the central nervous system to coordinate the movements of individual joints and muscles based on sensory feedback. Motor control is represented in the ability to move and the quality of movement that a child has to maintain an unsupported upright posture in sitting or in standing (i.e. balance), and in the ability to move out of the static posture with control.

In children with CP, the brain damage results in disorganised and delayed neurological mechanisms of postural control, balance and movement. This generates motor patterns that are inefficient and uncoordinated, which are indicated by an overall motor functional delay and abnormal performance [10, 11]. Altered motor control will impact on a wide spectrum of functional activities including the upper limbs (e.g. self-feeding), the lower limbs (e.g. walking), but also in the trunk and head (e.g. remaining seated or standing without external support).

As described above, the GMFCS provides a classification and general overview of the motor involvement of the child with CP; however, detailed assessment of the altered motor control is necessary to address the child’s functional difficulties. Assessments of motor function in CP generally determine how function varies over time in relation to the motor development and functional abilities of a healthy child. Two relevant examples of this are the Gross Motor Function Measure (GMFM) and the Chailey Levels of Ability; the GMFM subjectively assesses motor function from the variety of activities a child can accomplish [18], while the Chailey Levels of Ability provide a consistent method of analysing the observed posture for the prescription of treatment and equipment [20].

The GMFM assessment comprises activities in five dimensions: 1) lying and rolling, 2) sitting, 3) crawling and kneeling, 4) standing and 5) walking, running and jumping. The original version of the GMFM comprises 88 items (GMFM-88) and was designed and validated for children with CP. It uses a four-point scoring system for each item[3] with specific scoring descriptors detailed in the administration and scoring sheets. The GMFM scores are summated to calculate raw and percentage scores for each of the five dimensions. Changes in scores over time provide an indication of change and variability as a consequence of motor development and therapeutic interventions [18]. The GMFM-88 has been shown to have acceptable intraclass correlation (ICC ≥0.75) [21] to excellent (ICC= .952-1.000) [22] respectively for intra- and inter-rater reliability .

The Chailey Levels of Ability provide a consistent method of analysis of the observed posture for the prescription of treatment and equipment. They review developmental progression and the detailed position of the limb girdles, head and limbs during lying (prone and supine), sitting (floor and box) and standing. A child's ability in each posture is defined in relation to loadbearing, movement and symmetry[4] [20, 23]. For all its components, the Chailey Levels of Ability have shown good reliability (Pearson Product Moment coefficient correlation >0.75) and good validity against the GMFM (correlation between 0.85 and 0.96 for the different positions) and the Alberta Infant Motor Scale[5] (correlation between 0.90 and 0.97 for the different positions) [20].

As a complement to these more general tests of motor function, there is a group of tests developed to specifically assess trunk control in sitting. These include the Trunk Control Measurement Scale (TCMS) [25] and Sitting Assessment for Children with Neuromotor Dysfunction (SACND) [26]. These validated but subjective assessments are generally conducted with the child sitting on a flat surface such as a bench (i.e. not the floor). Reliability studies have shown excellent inter and intra-rater consistency for the TCMS (ICC= 0.98 and ICC= 0.97 respectively) [25] and excellent for the SACND when using well-trained

[3] GMFM scoring system is 0 does not initiate the task, 1 initiates but completes less than 10% of the task, 2 partially completes the task and spans anywhere from completing greater than 10% of the task but less than 100% task completion, 3 completes the task.

[4] The Level of Ability is assigned according to nine components: 1 the parts of the body on which the child was loadbearing, 2 the ability to change areas of loadbearing, 3 the position of the pelvis, 4 the position of the shoulder girdle, 5 the position of the head and the chin, 6 the lateral profile of the body, 7 the effect of head movement on the trunk and limbs, 8 the ability to isolate movement of the limb, and 9 the predominant positions of the major joints [20].

[5] The Alberta Infant Motor Scale (AIMS) "details a child's motor development until walking independently. It is a 55-item scale detailing abilities in the positions of supine, prone, sitting and standing and was developed to identify infants who were falling behind in their motor milestones" [24].

raters (ICC= 0.999 and ICC between 0.996 and 0.998 respectively for inter- and intra-rater reliability) [27]. These tests are designed for children with mild neuromotor disabilities, as a pre-requisite is that the child can sit without trunk support for 5 minutes (SACND) and 30 minutes (TCMS); furthermore, the TCMS requires the child to have the feet free of support thus placing a further control demand. The TCMS and the SACND assessments include both static and dynamic (active) components to test postural control through a variety of tasks. Tasks range from holding the sitting position for 10 seconds with the hands resting on the legs, to reaching to the opposite side with one arm while the other remains resting on the leg.

A complementary approach to assessment of motor control is through the consideration of postural alignment and the strategies used to demonstrate and confirm control of the aligned posture in the presence of a neuro-developmental condition such as CP. This approach was first developed by Butler and Major in 1992 [28]. These authors consider the ability a person has to maintain a controlled vertical postural alignment of the head and trunk with no external support other than the primary support, usually a flat bench; these authors define this ability as active control of the neutral vertical head and trunk posture and it is a key principle underlying the Segmental Assessment of Trunk Control (SATCo) [29]. During the assessment of trunk control of children with motor disabilities, for example, support can be provided either by an external source (e.g. a toy that is held by someone else, or someone else hands on the child) or by any part of the child's own body (e.g. the thighs, the head, simply resting hands down on the bench or the hands themselves linked together in the air) (Figure II-1). Internal support is provided by collapsing the trunk into flexion or hyperextension to joint end-range and thus using internal structures such as ligaments to provide the support (Figure II-1). The presence of either external or internal support means that full active control of the unsupported aligned posture is not demonstrated and, in a child with CP, provides a clear indication of compromised neuromotor control[6]. Identification of neuromuscular control strategies used by a child with CP can optimise therapeutic interventions but a detailed assessment is required

[6] Refer to Chapter V for further details about the use of different strategies of control.

to understand at which point and under what conditions head and trunk control is compromised or lost.

The GMFM and the Chailey Levels of Ability enable treatment to be planned and equipment adjustments be made as the abilities of a child change over time; however, there are limitations when looking specifically at the quality of the movement or inferring a child's control status from these tests. The GMFM does not consider the characteristics of the movement, but only how much of a specific activity a child can accomplish. An example of this is the task "Sitting on bench: maintains, arms and feet free, 10 seconds" (item 34 of the GMFM-88) where a score of 3 (the highest score) will be given if the child is able to maintain a sitting position for 10 seconds with feet and arms unsupported, while a 2 will be given if the child maintains the position for 10 seconds with arms propping and feet supported. Although in this example the progression of function considers the use or not of arm support, the only reference to any aspect of control of the posture is that it should be 'stable', ignoring the strategies a child can adopt to maintain stability such as a subtle collapse into flexion. Although the Chailey Levels of Ability consider the symmetry of the position and the roundness of the back (e.g. during the assessment of floor or box sitting) it does not fully describe alignment. Furthermore, it takes no regard for the use of the hands as an external support and thus also has no specific components to demonstrate control status.

These constraints are also reflected in the complementary clinical tests (TCMS and SACND), where there is no consideration of the alignment of the trunk or the use of the arms to compensate for any trunk control deficit. These limitations could result in a therapeutic plan with goals that are not challenging enough to encourage progression, or that are too challenging and will result in altered postures or compensatory strategies to achieve a task.

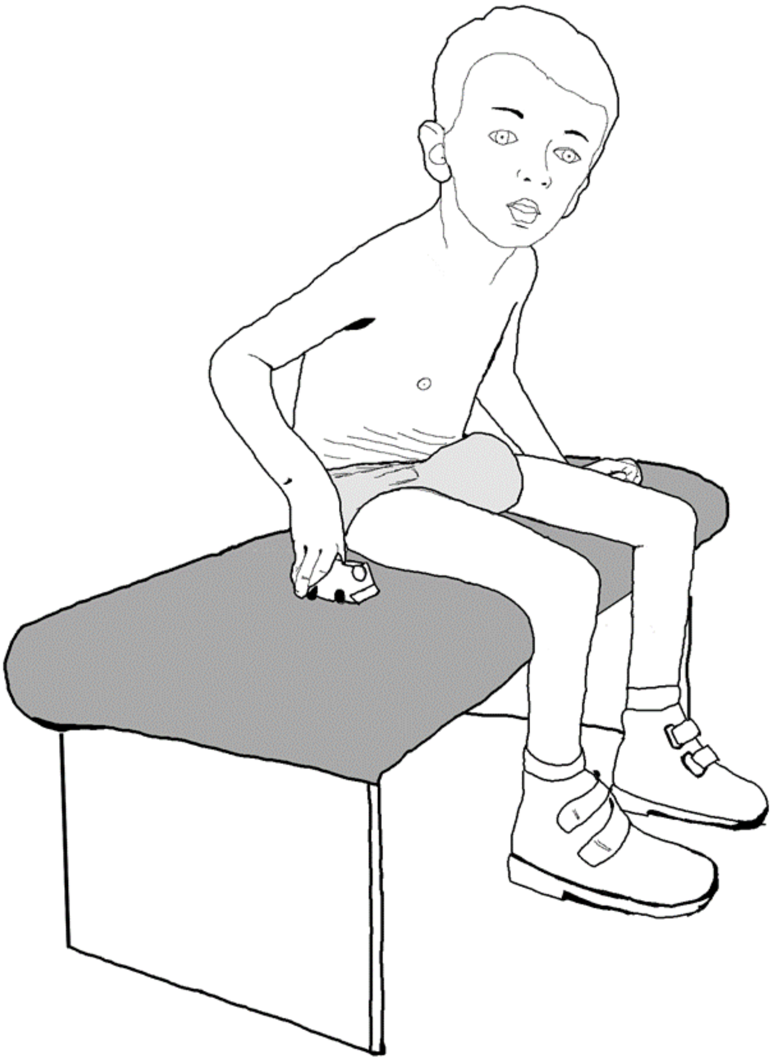

Figure II-1 Representation of a child sitting with a collapsed trunk and using his hands for support.

In contrast to the tests mentioned above, the SATCo [29] is designed to include children of all levels of disability and it considers the alignment of the trunk and the use of both internal and external support to define whether or not the child is actively demonstrating control of all or part of the neutral vertical posture. The SATCo assesses control at six discrete trunk segmental levels in addition to full trunk control, following the typical development of head and trunk control in the vertical posture (Figure II-2). A firm external manual hold is provided immediately below the assessed trunk segment giving a transient base that is both horizontally and vertically aligned [29]. This decreases the control demands for the child and ensures that the biomechanical demands are at a minimum[7]. At each segmental level, the SATCo assesses static, active and reactive control without external support[8]. These respectively represent the ability a child has to maintain a vertically aligned posture above the level of support for 5 seconds, to maintain a neutral vertical during head turning or arm movement and to remain stable during an external perturbation or to return quickly to vertical. The SATCo has shown excellent inter-rater reliability for the total data set (ICC = 0.84) and intra-rater reliability across all data sets and aspects of control (ICC = 0.98) [29]. It is, however, a subjective test. The SATCo thus identifies the specific trunk segmental level where the child is not demonstrating active control (the 'targeted segment'). Knowledge of the targeted segment further defines the support requirements for a child to learn to control his or her head and trunk. This therapy is called Targeted Training[9] (TT).

Although the tests described above have shown good to excellent reliability, they are based on a subjective assessment. In a clinical context, subjective assessments are a practical option. However, they can inadvertently introduce evaluator errors or inconsistencies, for example, as the result of an inexperienced observer performing the evaluation, or by a different interpretation of generic terms between assessors. These variations will then result in a confounded

[7] A firm external hold provides the child with mechanical stability that assures a condition of stable equilibrium even in the presence of perturbations. The degree of stability is directly related to the control requirements; the greater degree of stability generated by a base horizontally and vertically aligned, imposes less demands upon the active control system [30].
[8] As described by Butler et al. [29], Head control is assessed only statically and actively and hands and arms can be supported since they are below the assessed segment.
[9] For an overview of the therapeutic principles of Targeted Training and other therapies please refer to Chapter III.

judgement about the function and control abilities of a child. The limitations introduced by these errors and inconsistencies can, however, be overcome by the addition of objective quantification to patient assessment. Such quantification, using affordable and user friendly technologies such as the one used in the present project, can complement subjective assessments and help to eliminate potential variability between assessors.

5. Conclusion

Cerebral palsy is a common motor disability in childhood; it follows damage to the brain in early life and results in lifelong motor difficulties. Assessing how a child's function is affected as consequence of the motor involvement is essential to the development of an appropriate and comprehensive therapeutic plan. Although reliability studies have shown excellent inter and intra-rater consistency for all of the clinical tests mentioned above, they are nevertheless based on a subjective assessment. The development of methods to objectively quantify motor control, as developed in the present project, represents an opportunity to complement these subjective assessments giving a more accurate picture of a child's neuro-disability compromise and its changes over time. Furthermore, quantitative methods might also aid understanding of the experts' thinking process, by relating a concept or idea to an objective measure. The development of objective methods to assess control, which is the main objective of this project, represents a step forward to enlighten the identification of the key components of control. However, these methods, as considered in the 'Postural Alignment Assessment Methods' (Chapter IV), will need to be suitable for application in a clinical setting and for use with all patient groups, especially young children.

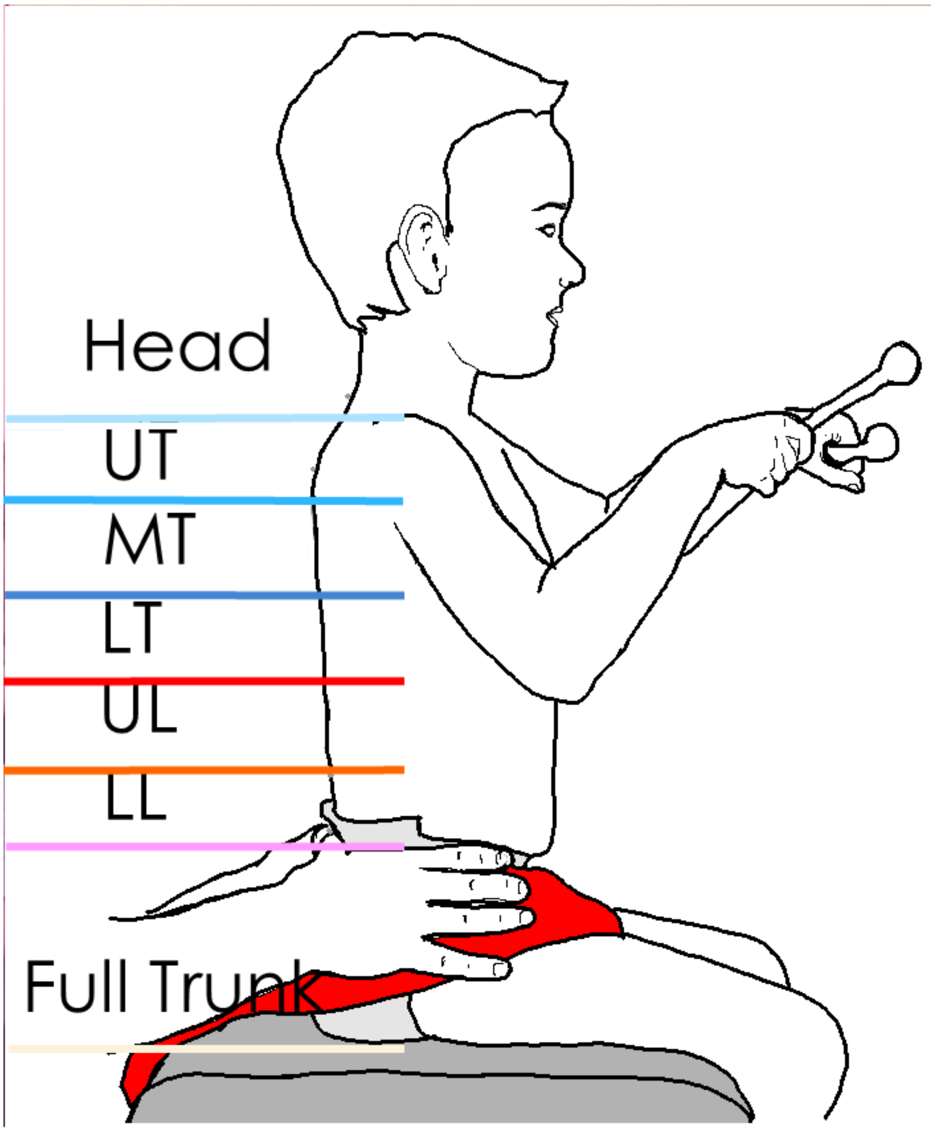

Figure II-2 Representation of the Segmental Assessment of Trunk Control (SATCo) segments.

Showing the distribution of the trunk segments where control is tested: Head (or cervical control) (Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Full Trunk in sitting (tested with no external support). Figure illustrates testing of LL control.

III. Targeted Training and Other Physiotherapeutic Interventions

1. Introduction

Brain damage in early life can result in lifelong motor difficulties associated with cerebral palsy (CP)[10] [4, 5, 11]. Infants and young children with CP are offered regular and frequent sessions of physiotherapy to address the motor control issues and to try and reduce the impact of the secondary musculoskeletal problems. In older childhood and teenage years, the physiotherapy input continues but the focus changes to training and assistance with functional independence, mobility and health-related quality of life. To do this effectively, treatment should be multidisciplinary, as well as including the patient and family and the community [31, 32]. In this context, physiotherapy plays a central role in managing the condition, focusing on function, movement and optimizing the child's potential [33].

Since the manifestation of the brain injury is particular to each patient, so the therapeutic approach has to be tailored individually and to change as the patient's needs change over time. Several therapeutic interventions exist that provide an overall framework to develop a programme for the specific needs of the child; nevertheless, these are not used in isolation. Additional strategies include, but are not limited to, postural management strategies, task-focussed active use, orthopaedic surgery and botulinum toxin injections.

This Chapter briefly describes the principles of the most common physiotherapeutic interventions that aim at improving gross motor performance such as the Bobath approach and Conductive Education system. There is also a description of Targeted Training therapy as an innovative therapeutic intervention that closely relates with the work developed in this thesis. Where possible, the evidence of the effectiveness of the different therapeutic interventions for children with CP is also described.

[10] Refer to Chapter II for a detailed description of the motor difficulties that are the result of Cerebral Palsy.

2. Bobath Approach

The Bobath approach proposes that normal or near-normal muscle tone is essential as a basis for reflexive movement in order to carry out activities of daily life. This approach considers that, in CP, the fundamental difficulty is the lack of inhibition of reflex patterns of posture and movement that results in abnormal muscle tone; thus a main goal of the Bobath concept is to facilitate the establishment of normal motor development and function together with the prevention of contractures and deformities [7, 34].

The Bobath approach, also known as Neurodevelopmental Therapy (NDT), was developed in the mid-20th century by Karl Bobath (a neuropsychiatrist) and Berta Bobath (a physiotherapist). This approach was one of the first to recognise that all patients with neurodisability have the potential for enhanced function, making the goal of treatment to work for what the person can do with minimal help [34].

The neurodevelopmental approach focused on the components thought most likely to be impaired as a result of a central nervous system (CNS) damage [7], i.e. the inhibition of reflex patterns and the abnormal muscle tone that impedes normal motor development. Physiotherapists use ‘handling’ i.e. positioning the patient in reflex-inhibiting postures, and guiding movement that “improves quality of tone and movement” [9]. Positioning and handling techniques aim to control various sensory stimuli and so to inhibit spasticity, abnormal reflexes and abnormal movement patterns [7]; in turn this is held to optimise the functional capacity of the child since normal or near-normal muscle tone is essential for effective movement to carry out activities of daily life [9].

NDT techniques are taught to parents and carers and incorporated into activities of daily life. For example, in rising to sitting from a supine position, parents are instructed to hold the child with his/her elbows extended and slowly pull up waiting for the child to actively raise his/her head; this handling would encourage the child to activate the flexor muscles of the head and neck. Parents are also taught to train their child to rise from a side-lying position if the child has an excessive extended head position in supine [35]; this manoeuvre will avoid the triggering of an increased extensor muscle tone that would prevent the child from maintaining a balanced sitting position. Teaching to parents and carers also includes instruction on ways to assist a child to achieve best performance, and to remove assistance when possible to maximise function [9].

Since it was first developed, the Bobath approach has been modified to take account of emerging knowledge in neuroscience, as well as expanding the concept based on the observation of children's performance following intervention. The original principles of the NDT were based on the assumption that the control and positioning gained from a 'reflex-inhibiting' posture would translate to movement and function; however, experience proved otherwise. Subsequent modifications in the application of the method showed how the reduction of spasticity in a static posture such as lying supine could be used to facilitate movement such as rolling to prone lying; it can then also be used for improvement of function e.g. if a child was to play with toys placed in front of him/her while lying in a prone position [7]. Furthermore, the NDT principles have been influenced by therapists' individual underpinning knowledge and the resources locally available to them. Although the 'Bobath concept' is used around the world as a common therapeutic technique for the treatment of CP motor difficulties, the way it is applied can vary from one practice to another. Most frequently, Bobath trained therapists tend to focus on a few of the constituent elements, but also to combine it with other techniques, making the application of the process more eclectic [7, 34]. This variability in the use of NDT is reflected in research findings.

Determining the effectiveness of NDT and demonstrating its effects in the inhibition of reflex patterns and in the improvement of movement has proved to be a difficult task. The variability among studies is compounded by treatments that have not been delivered in a standardised manner [7], making it difficult to consolidate the findings from different publications and to draw clinical inferences [32, 33]. Evaluating the effectiveness of the Bobath approach is further confounded because the procedures depended upon the skill level and preferred techniques of the therapists, which are not always clear in the published studies [7]. This scenario is made more complex by the variability of outcome measures used to assess the effectiveness of the Bobath approach interventions [7].

Limited evidence of the effectiveness of NDT is not only related to the varied ways of delivering the therapy, but, in common with other therapy approaches, it is also related to the high variability of presentation of CP, as described in Chapter II. Although the distribution of the movement disorder can be identified by the site and extension of the brain injury [15], the severity of the motor difficulties varies greatly among children. In research, this is reflected in low incidence and highly heterogeneous conditions of the children, which makes it difficult to demonstrate the impact of the research findings [7, 32]. This difficulty could be potentially overcome by a quantitative method of assessment where the measure of change that results from a specific intervention can be quantified in small homogeneous groups of children, rather than requiring study groups with large numbers of participants.

These limitations are reflected in the summary statement by Mayston [9] that "there is no conclusive evidence to show that it [Bobath therapy] is effective or what elements of the NDT approach are most beneficial" (pg. 150). Since this was written there has been no further conclusive evidence produced. Application of therapeutic interventions, both in a clinical practice and in research, should be based on clear principles and standardised administration procedures. The proposal by Mayston about 'elements' is an important factor; if the principles underpinning a therapy and the characteristics of those patients most likely to benefit can be established, then research demonstrating effectiveness or comparing therapies is more likely to give clear information. This, together with clearly defined measurable outcomes, could help to compensate for the low incidence and high variability conditions of the children.

In summary, the Bobath approach is a commonly used physiotherapy technique world-wide. It is based on the facilitation of normal muscle tone, through the use of positioning and handling, to improve movement and function. However, it requires skilled therapists for its most effective delivery, meaning that it is resource intensive, and there is no conclusive evidence of its effectiveness.

3. Conductive Education

Conductive Education (CE) was developed in Hungary in the 1940s by Dr Andreas Peto to assist children with motor dysfunction [8, 34]. CE is primarily a learning process based on a system designed to promote independent motor functioning as well as the development of cognitive, communicative, social and activity of daily living skills. In the 1940s, children in Hungary were not permitted to attend school unless they could walk independently and were continent. CE was developed to address these issues and so enable more children with disability to receive schooling. This contributed to CE being based on an educational approach to rehabilitation rather than a medical model of intervention [8, 9, 34, 36, 37].

Thus, the main features of CE focused in the attainment of 'orthofunction'[11] enabling children to attend school with maximum independence [8, 37]. In the traditional model, CE was carried out in a group educational setting with school-age children monitoring and encouraging each other, while a conductor (a unique profession that incorporated both teaching and therapy skills) led the group and provided a motivating and supporting environment [8, 9, 34].

In this high intensity method, children lived in a boarding-school environment and spent all their waking hours practising different movement skills to achieve the educational goals of the group. Each goal was broken down into a series of skill steps/basic motor tasks to make it more manageable for the children. Tasks were accompanied by a 'rhythmical intention' of the movements, provided both by music and by the conductor and children's verbal repetition, again reflecting the regular Hungarian education at that time. As the main purpose of this method was to encourage children to walk independently, the use of walking aids was discouraged. Only the use of wooden slatted beds and ladder-back chairs were allowed for assistance during the sessions [8, 34, 36, 37]. CE relied on the child problem-solving for him/herself in order to make progress [36].

This method has been widely adopted in the UK and Australia but modified from the original concept to be more compatible with modern daily life [34]. The

[11] 'Orthofunction' was defined as the "ability of the child to participate and function in society despite his or her disability" [8], which is "functioning adequately in society without aids" [37].

literature shows how the principles of CE are applied by therapists and teachers in different settings, but the total CE programme, as developed in Hungary, is not implemented to its full extent [8]. The major change is a reduction in the intensity of the sessions. In addition, the CE principles are now usually combined with other therapeutic approaches and the walking aids the children normally use are permitted during the therapy sessions. The rhythmical intention and the broken-down presentation of movement skills are, however, maintained [8, 37].

Although some publications have shown positive results from the use of CE as a therapeutic method to improve motor skills in children with CP [38, 39], these studies have been dismissed by other researchers as weak evidence [8] and biased [37]. Quality research showing the impact of the CE method is sparse making it difficult to define the overall effectiveness of the method [8, 37, 40]. Evaluating the advantages of CE over other therapies has had similar limitations to those cited above for the Bobath method. Published studies have again used a variety of outcomes measures to show changes associated with the therapeutic intervention [8, 37, 40]. Furthermore, these studies generally included only small numbers of children in both intervention and control groups making heterogeneity a major problem with resultant difficulty in generalisation. Few researchers have followed the principles of CE from the original guidelines and contrasted the results with other interventions [41, 42]. Findings have shown favourable outcomes for CE when compared with less time-demanding interventions but it is not clear if the improvement is the result of the CE therapy, or of the high intensity intervention.

Although current therapeutic interventions include CE, the original principles have been modified to conform better to the daily routines of children and families in different countries and current life, and to merge with other therapeutic strategies. These changes have made it difficult to define the real impact that CE has in the improvement of motor functional skills.

In summary, present day use of CE is, with very few exceptions, a variation of the original concept, a concept which was based on a specific educational regime of 70 years ago. There is no conclusive evidence of the effect of CE or of its superiority to any other approach.

4. Horseback Riding

Horseback riding as a therapeutic programme refers to the use of equines' movement as a tool to stimulate motor, visual proprioceptive, vestibular and tactile systems. The potential of horseback riding for patients with neurological disorders and other disabilities was first recognised in the 19th century, but it was in the early 1950s when horseback riding as therapy spread from Western Europe to other parts of the world [43].

Horseback riding therapy as an intervention has been used with children with CP and is believed to improve gross motor function [44]. The literature describes two types of therapeutic riding programmes: hippotherapy and therapeutic horseback riding (THR). Hippotherapy uses the horse to achieve physical, psychological, cognitive, behavioural and functional goals. In hippotherapy a physical or occupational therapist guides a child's posture and movement while riding, sitting on the horse behind the child if necessary; this implies that the horse is used as a tool to influence the child's posture, balance, coordination, strength and sensorimotor systems [43-45]. In contrast, THR is a recreational activity provided by a non-therapist riding instructor. In THR the participating child plays an active role in controlling the horse. The child engages in riding activities led by the riding instructor as a form of exercise to improve coordination, balance and posture and to encourage development of sensory and perceptual motor skills [43-45].

The many studies on the effects of hippotherapy and THR in children with CP have been consolidated by Whalen and Case-Smith [44] and by Tseng et al. [45]. The authors of these reviews agree that studies have shown the benefits of both hippotherapy and THR in reduction of muscle tone, increase of postural symmetry, and promotion of postural stability in children with spastic CP. Moderate to large treatment effects have been demonstrated as result of the interventions [45]. However, there are several limitations that have made it difficult to generate a definitive recommendation about the use of horseback riding as a therapeutic intervention in children with CP.

In common with research on other therapies, studies assessing the effects of hippotherapy or THR have presented relatively small and very heterogeneous samples, generally between 3 and 17 children (maximum 35 children [46]) in the intervention group and aged between 2 to 18 years. Although most study participants had spastic CP, they encompassed all levels of the Gross Motor Function Classification System (GMFCS I-V)[12]. The exception was the study by Hamill et al. [47] which was limited to children of GMFCS Level V but included children with very varied diagnoses.

Whalen and Case-Smith and Tseng et al. [44, 45] have identified studies which showed that children with milder spastic CP (GMFCS I-III) were more likely to have significant improvements in gross motor function and postural control as result of horseback riding, and that these could be achieved with sessions of 45 minutes once per week for at least 8-10 weeks. Children with mild functional deficits present motor control skills that allow maintenance of a floor sitting position (GMFCS III, 2-4 years), or ability to walk in most settings –indoors and outdoors- (GMFCS I, 6-12 years) in contrast to children with greater functional deficits (GMFCS IV and V). Maintaining a sitting position on a horse while moving can represent too great a challenge for children who have not developed the functional skills to maintain upright sitting, even with the support of the therapist. Nevertheless, the horse movement provides a continuous stimulus that can favour the improvement of postural control in more able children with the position on the horse providing a stable base of support (given by the pelvis and lower limbs position) and favouring a vertical alignment of the head and trunk.

In summary, horseback riding is used as hippotherapy (therapist guided) or therapeutic horseback riding. Both use the motion of the horse to stimulate motor, visual proprioceptive, vestibular and tactile systems and so improve motor control and function. Although there have been some positive results in particular groups of children with CP with interventions usually taking place for only 1 hour a week, it is difficult to attribute the effects to horseback riding therapy rather than the child's routine therapy.

[12] Refer to Chapter II for a detailed description of the classification (Table II-2).

5. Constraint Induced Movement Therapy (CIMT)

Constraint Induced Movement Therapy (CIMT) is a treatment delivered to improve functional performance of the more affected upper limb in children with hemiplegic CP. CIMT is based on the view that the affected arm and hand function is limited because of lack of experience and practice [35]. Therapy involves restriction of the less affected upper limb so the child is obliged to use the affected arm to carry out tasks and so enhance perceptual-motor function and motor learning within that arm and hand [35]. This approach is based on brain plasticity, which is the ability to recruit other areas of the brain, often adjacent to the focal injury, to perform functions that have been lost [48]. In CIMT brain plasticity is enhanced through sensory and motor inputs that generate "changes in brain synapse configuration resulting in improved motor performance" (pg. 184) [48].

Studies that have assessed the effect of CIMT have mainly included children 4 to 18 years [49, 50], but some recent studies have also included children under 2 years [51]. Studies including older children have shown a medium effect on improving arm function after CIMT [49, 50] while infants between 6 and 18 months demonstrated significant improvement in fine and gross motor performance [51].

However, the study protocols described vary in frequency and duration of the immobilization (which can include partial and full arm casts, splints and soft mitts), as well as of the treatment interventions, which may influence the results reported. Furthermore, most of the comparative studies have an intensive CIMT intervention that is not equivalent to the control intervention. This could suggest that the significant differences between the CIMT and the other interventions could have been the result of the intensity of the intervention more than the therapy itself [49].

Although the studies that have evaluated the efficacy of CIMT in children with hemiplegic CP have generally shown positive results, there remains lack of clarity about the ideal protocol for intervention. Authors seemed to agree, however, that home-based intervention had larger positive effects that clinic-based interventions. Home-based interventions offer the child the opportunity to learn new skills in an environment and with objects that are familiar; therapeutic activities delivered by the parents or carers (guided by the therapist) can easily be included in a daily routine.

In summary, CIMT aims to oblige use of the more affected arm and hand by restricting the less affected limb; this is held to enhance perceptual-motor function and motor learning. There is some evidence for the effectiveness of this approach but this may be age dependent with younger children making greater progress.

6. Targeted Training

Targeted Training (TT) is a therapeutic approach for the management of motor control deficits that is based on biomechanics [52]. It was first developed in the early 1990s by Butler and Major and used at The Movement Centre (Oswestry, UK) assisting patients from around UK. TT focuses on the acquisition of vertical control of the head and trunk as an essential prerequisite to performance of everyday activities[13] [53]. This differs from other approaches that take a child through a developmental process of learning to lift the head when lying prone, to roll, to come to sitting, kneeling and eventually to standing with the assumption that this sequence will lead to control of the upright posture [54]. Another difference between TT and conventional physiotherapy, such as Bobath or Conductive Education, is that these therapies treat the trunk as a single unit with control learning taking place simultaneously throughout the whole trunk. In contrast TT simplifies this learning process by using a sequential cephalo-caudal, segment-by-segment approach[14] mimicking the process of typical development of head and trunk control during the first 12 months of life [53, 55-57].

This process of cephalo-caudal motor learning has a logical mechanical-control basis. There is no mechanical point to controlling the head unless the supporting structure is controlled, either actively or by external support. Since the structure is mechanically unstable, it is difficult to control the lower segments in an aligned

[13] Targeted Training considers also the motor control of the lower limbs. This review of TT focuses on the head and trunk as this is the subject of the current project.
[14] The segments as defined for the SATCo and the TT therapy are: Head (comprising head and neck), (Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Full Trunk.

balanced posture if the upper segments are uncontrolled. The uncontrolled upper segments present an unknown mechanical disturbance to the lower segments. Evolution has ensured that the primary sensory balance organs are in the head and this results, developmentally, in control learning from the head down. Children with CP, given their sensory balance organs are in the head, cannot control lower segments unless the head is controlled. This distinguishes TT from other physiotherapy approaches, none of which have this foundation of principle and lack a convincing mechanistic basis.

The Segmental Assessment of Trunk Control (SATCo) is used to define the trunk segment where control learning should commence. The SATCo systematically assesses Static, Active and Reactive control in sitting at six segmental levels and free sitting, identifying the highest (most cephalo) segmental level where control is no longer demonstrated[15]. This is called the 'targeted segment' and is the segment where control training commences [29]. For the TT approach, neuromuscular control is demonstrated when the child can maintain a vertical aligned position of the segment under test and all segments above (Static control), is able to voluntarily move out of the position and return to it (anticipatory or Active control), and can respond to external perturbations by returning quickly to the vertical posture (compensatory or Reactive control). Control is only credited if there is no use of the upper limbs for support or any strategy of internal mechanical support e.g. collapsing the lumbar spine [29].

To facilitate the learning of vertical control at a specific level, TT generally uses specialist equipment that provides firm support and can be individually adjusted to ensure a vertically aligned position of the child's body of the targeted segment and those segments above and a horizontal pseudo-base of support (defined as the segment immediately below the targeted segment) [55, 58]. This provides security and stability that allows the child to move freely above the support (Figure III-1).

As a therapeutic intervention, TT aims at the improvement of motor control based on functional goals established at the beginning of the intervention. This is no different to other therapies but the biomechanical basis of TT gives the therapy a

[15] Refer to Appendix A for a detailed description of the SATCo test.

different approach to the achievement of functional goals. This is reflected in the identification of the targeted level, the design and development of the specialised equipment, and the specific care to ensure the child's optimal positioning in the equipment.

This relatively new therapy is the subject of research projects world-wide but not currently available as a regular clinical service other than in the UK. Although in recent years it has been considered as an adjunct therapy [34], there is little published evidence of its efficacy. In 1998 Butler [53] presented a preliminary report of the effectiveness of TT and its potential in initiating or accelerating improved movement control of the trunk in children with CP. This study presented a case series of six children with CP (2 years, 5 months to 7 years, 5 months) and showed that all six children gained independent sitting balance within 12-25 weeks of the start of TT.

Recently, Curtis et al. [59] presented a randomised control trial where the effectiveness of TT was compared to conventional physiotherapy. In this study, twenty-eight children with moderate-to-severe CP (GMFCS III-V) were randomly allocated to the intervention (n=14, 8 years, 5 months) or to the control group (n=14, 8 years, 6 months). Results showed no statistical difference between the two groups in the improvement of motor function (Gross Motor Function Measure – GMFM and Pediatric Evaluation of Disability Inventory – PEDI)[16]. However, there was a greater reduction of anterior-posterior head sway in the intervention group at the end of the training program.

[16] Refer to Chapter II for a description of the GMFM.

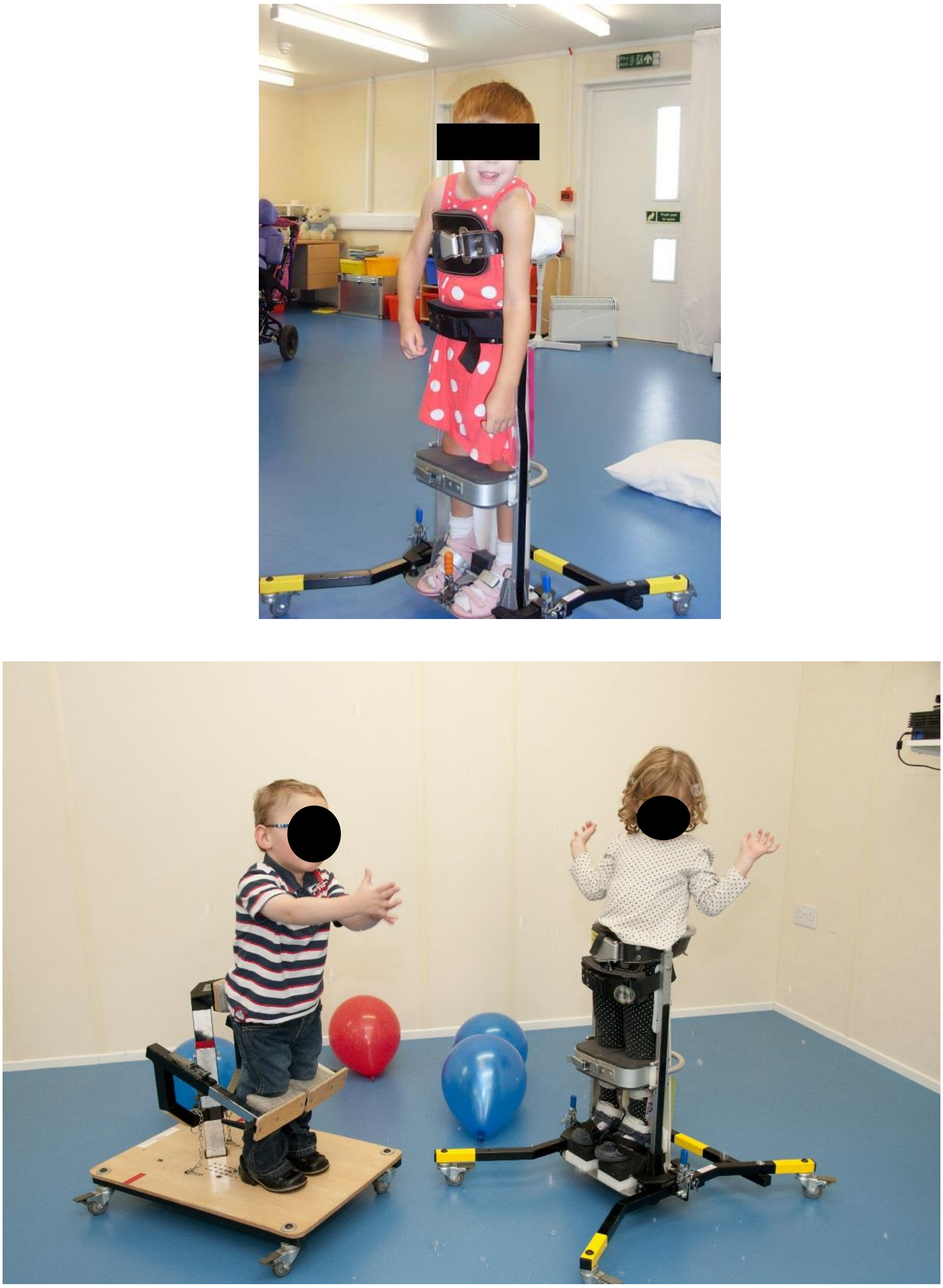

Figure III-1 Examples of Targeted Training equipment.

Showing two different supports for training: top learning Upper Thoracic control, bottom learning control of the pelvis and thigh segments (left) and learning control of the Lower Lumbar segment (right). (Photos courtesy of The Movement Centre, Oswestry).

Although these two studies show a striking difference in the findings, there are important variations in the methods that can help to explain the differences. Children in Butler's study were younger than those in Curtis et al., this age difference may be reflected in the potential a child has to gain motor skills. Even though not reported by GMFCS level, the children in the first study had normal head control, while the majority of children in Curtis et al. had only fair to poor head control; this, combined with a shorter intervention period, could account for the poorer results reported by Curtis [59]. As these authors stated, "interventions aimed at the achievement of head control are lengthy. Typical periods of Targeted Training are around 9 months for children with deficits in trunk control and 18 months for those working on head control" (pg. 8); a shorter intervention (6 months) might not allowed the improvements in head control to become functional and to produce lasting change.

In summary, Targeted Training therapy is an innovative technique that aims to improve motor control of the individual in a vertical position in order to improve overall functional ability. This segmental approach considers the increased difficulties that a child with CP may encounter when learning to control a larger part of his/her body. The use of specialised equipment to ensure a true vertical alignment in standing and to localise the training to one poorly controlled segment of the head-trunk column, makes the acquisition of control a less demanding task. There is, as yet, no evidence of the superiority of TT over any other approach and research to fully understand the effects of TT and to define the best protocol of intervention is still required.

7. Conclusion

This Chapter has briefly described the principles of the most common physiotherapeutic interventions for children with cerebral palsy focused on the improvement of gross motor performance (Bobath and Conductive Education) or on upper limb function (Constraint Induced Movement Therapy). The principal characteristics of some less common therapies that use external tools to provide motor and sensory stimulus are also described (horseback riding and Targeted Training).

Although these approaches, or parts of their principles, are applied daily in the treatment of children with CP, their supporting evidence is generally weak. Weak evidence does not enable full understanding of the impact of a specific intervention (or therapeutic plan as a whole) to address the motor difficulties of CP.

Weak evidence can be the result of the combination of different factors. In first place, it can be associated with the wide spectrum of manifestations of the brain injury, as described in Chapter II, that results in study groups with few numbers and consequently low statistical power. Weak evidence can also be related to variations in the intervention procedures, which makes it difficult to generate a definitive recommendation as it cannot be certain that the different protocols were following the therapeutic principles in precisely the same way. In addition, and more importantly, the outcome measures selected to evaluate the efficacy of a specific therapeutic intervention, can also be a contributory source to the weak evidence of the studies.

The studies reported in this Literature Review generally used assessments that, even if standardised, are based on a subjective appreciation of the child's functional abilities; the functional abilities observed are then used to infer the motor control status of a child. This difficulty could, however, be overcome by the complementary use of an objective assessment of motor control. Complementing the clinical evaluations of motor control, as proposed in the present project, could help in understanding of the effectiveness of a particular intervention, or of the interactions of different approaches in a complete therapeutic plan. Furthermore, such objective measures could help to compensate for the heterogeneity of participants in research.

IV. Assessment Methods of Postural Alignment

1. Introduction

The concept of body alignment is closely related to that of posture assessment in an upright position such as standing. The features of the ‘ideal posture’ during standing have been generally accepted and are commonly used as reference during physiotherapy assessments. However, these descriptions come from a subjective ‘common knowledge’ where there is a marked lack of quantitative evidence to support them [60] and a continuous use of general terms to describe the position of different body landmarks in relation to a reference. Use of these general terms allow a wide range of interpretation and thus permits differences between observers. This further compounds the subjectivity of posture assessment. When considering sitting posture, there is even less information available; there is no ‘ideal posture in sitting’ and the assessment tends to be limited to a comparison with the observations of standing posture.

A given body alignment in the upright position is most usually associated with musculoskeletal characteristics, such as joint hypermobility or joint limitation. However, an altered postural alignment in standing or sitting can also reflect a deficiency of neuromuscular control. In the presence of a neuromotor disability, such as stroke or cerebral palsy, poor control can result in the use of altered postural strategies to maintain an upright balance in the presence of inadequate control. These strategies are evidenced by a modified body geometry, for example by the spatial relationship of the head to the trunk and in relation to the base of support.

This Literature Review focuses on the potential of various methods of assessment of postural alignment, i.e. the geometry of posture, in a routine clinical context such as physiotherapy, and their applicability for patients of wide age range and differing pathologies. This includes young children and those patients less able to actively co-operate. The review particularly focuses on sitting posture where the information is available, since this is a fundamental posture of functional importance. The applicability of these methods in the assessment of motor control, i.e. the means of maintaining a given alignment, has also been considered. A summary is provided in Table IV-1.

2. Clinical Assessment

Traditional assessment of posture in a clinical context is based on visual observation. An experienced observer estimates the position of the skeletal structures by observing the contours of the body [1] and relates the relative positions of body segments to the ‘ideal alignment’ that is represented by an imaginary vertical line of reference or ‘plumb line’ [1] (Figure IV-1). Typically, a lateral view of the person is used to describe posture during quiet standing, but for completeness, a posture assessment should include an anterior, a posterior and both lateral views during standing and sitting, and in prone and supine while lying [1, 61, 62].

In the literature, there are clear descriptions of how the different landmarks of the body should relate to the plumb line during a standing assessment when the ideal alignment is achieved. However, general terms as “slightly posterior” or “just in front” are commonly used, allowing a wide range of interpretation and discrepancy between observers. The situation is compounded by the fact that the position of the reference or plumb line is related to landmarks that are not visible “the plumb line should be aligned so that it passes […] through the vertebral bodies of the lumbar spine, anterior to the vertebral bodies of the thoracic spine, through the tip of the acromion process in the shoulder” [1, 63]. This variability is reflected in the findings of a limited number of studies that have evaluated the reliability of the conventional postural assessment. Fedorak et al. [64] found fair intra-rater reliability (k=0.50) but poor inter-rater reliability (k=0.16) when a group of clinicians, including chiropractors, physiotherapists and orthopaedic surgeons, evaluated the posture of photographed subjects. Similarly, Iunes et al. [65] found that when three physiotherapists performed a live posture assessment some of the features evaluated showed no agreement ($p \leq 0.05$) between observers or only very weak ($p<0.6$) agreement.

Descriptions of an ideal sitting posture in a clinical context are limited to a general explanation of the foot position on the floor and the general angle of the knees. This gives a wide window of interpretation, which can result in a large discrepancy among assessors.

Traditional clinical assessments of posture are easy to apply in all groups of patients and require very basic instruments, if any. However, the limitation in these methods of describing posture is the introduction of observer variability. This limitation can be overcome by objectification of the assessments.

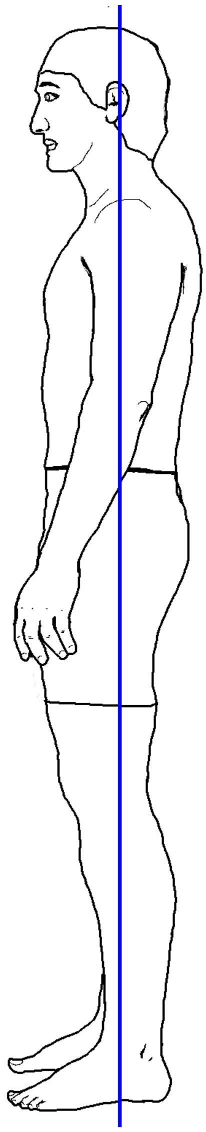

Figure IV-1 Plumb line.

A plumb line (in blue) is a simple device that is used as a reference to determine whether the anatomical landmarks of the person being tested are in the same alignment as the corresponding points in the standard posture [1].

3. Radiograph

The radiographic image or radiograph is a ‘photographic negative of the object being x-rayed’; the relative shades represent how much of the x-ray beam is blocked by a specific part of the body [66]. Radiographs are considered the gold standard to assess deviations of the spine and the measurement of angles of spinal deformities; radiographs, per se, are not quantified but allow measurements to be taken. Radiographs have been used as a method for describing, quantifying and classifying common variations in the sagittal alignment of the spine and pelvis of healthy young adults in standing [67], or to determine relationships between the vertical line of reference and the pelvic and spinal curves [68, 69]. Anatomical landmarks can be identified from the lateral radiographs to divide the spine into sections thus clarifying the identification of curves. In general, the main spinal curvatures studied, thoracic kyphosis and lumbar lordosis, are defined from the point of inflection between the kyphosis and the lordosis while their curvature is calculated by a variety of methods[17]. The position of the pelvis, on the other hand, is described jointly by the pelvic slope, the pelvic tilt and the pelvic incidence[18] [67-69].

Roussouly et al. [67], have used these measurements to identify the spinal curves of healthy participants and classify them into groups in an attempt to understand the relationship between spinal curves and the development of lumbar pain. There have also been some studies where radiographs were used to validate different methods aiming to reduce radiation exposure while still permitting the measurement of spinal curves and monitoring the progress of spinal deformities. A pertinent example of this is the study by Leroux et al. [71] which evaluated the accuracy of a non-invasive anthropometric approach for the measurement of kyphosis and lordosis. The anthropometric estimation of the sagittal curves of the spine was based on the detection and marking of specific spinous processes and then using a trigonometric model to calculate the curves. These estimations were

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[17] Tangent circles are used to model the curve with the main curvatures defined as two arcs of a circle, one above and one below the apex of the curve [67-70].

[18] Pelvic slope is the angle of inclination of the surface of the first sacral vertebra (S1) relative to the horizontal axis. Pelvic tilt is the angle between the vertical line originating at the centre of the axis of the femoral heads and the line from the same point to the middle of the superior endplate of S1. Pelvic incidence is the angle between the perpendicular to the sacral plate at its midpoint and a line to the axis of the femoral heads.

then compared with the measurement of the kyphosis and lordosis from lateral radiographs. Leroux et al. [71] found that there was a good relationship between the kyphosis and the lordosis angles calculated by the two methods. This was reflected by small relative (3°, -1°) and absolute (5°, 6°) mean differences and a strong correlation coefficient (r=0.89, r=0.84) for the kyphotic and the lordotic curves respectively.

Although it was noted that the lumbar angles presented a larger range when calculated using the anthropometric estimations, making it difficult to analyse the accuracy of a non-invasive technique from a clinical point of view, Leroux et al. [71] demonstrated that spinal curvatures can be calculated with accuracy using surface markers. However, this method has been used only with healthy adults to date and the need to remain perfectly still renders it of little value for assessment of the young child.

Radiographs remain the preferred method for quantitative evaluations of the spinal curvature and are primarily used for the assessment of spinal pathology. Although studies have positively related radiological findings to postural and occupational habits [72, 73], posture is generally a secondary consideration in the analysis of the images. In addition, due to the radiation exposure, the complexity and the cost, radiographic evaluation of posture is not a viable method for routine assessment in a clinical physiotherapy setting.

Radiographs remain an inadequate method of assessing upright control, as a single static image is not enough to represent a dynamic task. However, radiographic images can assist in the understanding of the anatomical characteristics which may compromise the acquisition of an upright posture.

4. Photograph

Photographs are static images (analogue or digital) which capture the position of a body at a specific instant. These have been used to link anatomical landmarks and give angular measurements, which has allowed a quantitative assessment of posture [65, 74]. Although some studies have used photographs to quantify posture through the digitalising of the x and y coordinates of the relevant anatomical landmarks, or of the marks placed over them, there is no standardised definition of the angles that can be measured using lateral and posterior photographs. From lateral photographs the different angles calculated to describe posture vary from the general trunk angle [74], to the angles of the separate regions of the spine [65, 75, 76] in standing, and the pelvic tilt and the angle between the pelvis and the femur during sitting [77]. However, there appears to be no defined standardised method of calculation of angles from photographs.

Dunk et al. [75] looked at the reliability of upright standing posture in adults, evaluating the reliability calculations of the cervical, thoracic and lumbar segments angles in relation to a vertical reference[19]. The authors concluded that standing posture exhibited poor to moderate reliability based on spinal angles being measured from the vertical.

In view of the previous findings, Dunk el al. [76] used what they defined as a ”biologically relevant measure” to calculate the angles of the segments in an attempt to improve reliability. A biologically relevant measure implied that the angles of the segments were calculated in relation to the immediately inferior segment[20]. This second study resulted in improved reliability of posture assessment in the sagittal plane.

Similar to Dunk et al. (2004) [75], McEvoy and Grimmer [74] used sagittal plane photographs of typically developing children (5-12 years) to calculate several angles (trunk, neck, gaze, head on neck, and lower limbs) to assess differences between repeated measures of upright posture[21]. In contrast to the findings by Dunk et al. [75], McEvoy and Grimmer [74] found that standing posture did not change significantly on repeated testing. These improved results can be related

[19] Markers were taped to the skin of the back of the participants to extrapolate the joint centre of each segment. The joint centres were then connected to represent the cervical (from the digitalisation of the ear canal to C7), the thoracic (from C7 to T12) and the lumbar (from T12 to L5) segments. Angles were calculated as the deviation of each vector from the vertical reference line.

[20] The marker coordinates were used to create vectors and the angle between the vectors was calculated using the algebraic dot product.

[21] The digital coordinates of the markers were used to calculate the angle; all the angles were calculated between the drawn lines that joined two markers with the exception of the trunk angle (from C7 to greater trochanter in relation to a vertical passing through this) and the lower limb angle (represented by the line between greater trochanter and the ankle, with the vertical at the greater trochanter).

to the amount and specificity of instructions given to the participants by McEvoy and Grimmer. However, it should be also noted that McEvoy and Grimmer took two measurements on the same day without removing the markers between the shots, thus reducing marker re-placement error. Taking repeated measures without removing-replacing the markers, as done by McEvoy and Grimmer [74], eliminates a source of error; then the angles measured truly reflect the posture of the child.

Photographs to assess posture have also been used in sitting. Alm et al. [77] measured posture from posterior and lateral photographs of males with complete spinal cord injury when sitting in a relaxed and in an upright position. The information recorded from the lateral photographs included the calculation of the pelvo-femoral angle (between the anterior superior iliac spine –ASIS, greater trochanter[22] and lateral tibial condyle), and the anterior tilt of the pelvis (from the ASIS marker to the greater trochanter and the vertical line passing through it). The information collected from this particular study helped the researchers to achieve a more comprehensive view of sitting of patients with spinal cord injury. Having a clear understanding of the position of the pelvis during sitting can be essential to understand the compensatory mechanisms to achieve upright sitting in patients with spinal cord injury or any neuromuscular disorder.

Although the use of photographs to quantify posture has been little used in research, this method can, nevertheless, offer a clinically relevant outcome requiring only low cost equipment and minimal preparation and disruption for the participant. In general, however, photographs will only represent the body configuration at one instance in time, while posture results from the interaction of systems and forces and is better assessed considering the ability to maintain it in time. Furthermore, as with radiographs, the posture capture during a single image does not provide enough information to assess the control a person has.

[22] Referred to by Alm et al. [77] as trochanter major.

5. Videos

Videography is a method of recording posture and movement patterns for continued periods of time. Videos are commonly used alongside a motion analysis system in biomechanics research laboratories and in the field to perform quantitative analysis of a specific action. In sports and exercise, videos allow recording of movement without any interference with the individual, such as marker attachment. This means that they are ideally suited to quantitative study of movement analysis in competitive situations [78], for example in running or high jumping, but, importantly, are also ideal for the study of postural alignment of the young child or patients who are less able to co-operate with instruction.

Despite this potential, the use of videos in clinical contexts has generally been restricted to gait analysis [79, 80] and to the provision of complementary clinical qualitative information in studies of balance and posture [81-83]. The 2011 study by Saether and Jorgensen used videos to examine the reliability of the Trunk Impairment Scale [83]; videos facilitated the reproduction of previously recorded assessments to a group of observers, but no further analysis was performed with them. Boxum et al. [81] limited the use of videos of infants to classify the success of reaching movements in sitting and to complement the electromyography (EMG) information. Similarly, Philippi et al. [82] recorded videos of the general movements of infants while simultaneously using a magnetic tracking device; the videos were only used to validate an automatic assessment tool developed against a specific clinical assessment. However, the information from the videos was not quantitatively analysed in any of these studies.

Overall, there is little information about the use of video in a clinical context for quantitative analysis. Khadikar et al.[84] used video analysis for the assessment of functional range or motion of the shoulder in relation to functional tasks finding that the use of video represents a viable quantitative clinical tool for assessment of functional range of motion. This approach, however, has not been implemented much further in assessments in clinical contexts. There is even less information that shows its application in relation to posture and alignment in standing or in sitting, or in the assessment of motor control. The development of analytical tools such as Dartfish[23] (Dartfish 7, TeamPro 7.0), means that the use of video in a clinical context now has much greater potential for quantifying and validating clinical tests and therapeutic interventions. An example of this is the work developed by Womersley and May [85]; they used Dartfish software to analyse video and evaluate the relaxed sitting posture of adults with and without back pain. However, the results presented do not place emphasis on the quantitative analysis of the lumbar curvature or the characteristics of the posture, but are limited to the relation between back pain and sustained sitting postures. In relation to the video analysis, the authors recognised the importance of having the same person digitalising the markers, and reported an average discrepancy of 0.31°.

6. Rastersterography

Surface topography systems, such as DIERS (Formetric 4D system, Diers Medical System), are techniques of optical measurement developed to perform analysis of patients' backs. They provide a fast and radiation free image of the spine position [86, 87] supplementing clinical examinations in orthopaedics and biomechanics [86-88].

The surface topography[24] device takes a series of digital pictures (2 per second over 6 seconds [89], 9-10 in a second [88]) of the back of a person in standing. The images acquired are evaluated and averaged correcting for any movement during the data acquisition to calculate a series of parameters that represent the main spinal characteristics (e.g. kyphotic and lordotic angles, trunk length and trunk inclination) [86]. Nevertheless, as reminded by Betsch et al., "posture is not a static but a dynamic process because the human back shape depends on many dynamic factors like muscle tonicity and position of the vertebral joints". This

[23] Refer to Chapter VIII for more information about Dartfish.
[24] Surface topography systems project horizontal lines of white light (raster lines) on the back of a standing patient. A digital photo of the back is taken to assess pinpoints surface asymmetry and identify bony landmarks. A surface reconstruction of the back is then performed by transforming the lines and the corresponding landmarks into a three-dimensional (3D) representation. This is then compared to a database containing thousands of measurements of patients with scoliosis [89, 90.]

consideration generated, in recent years, the development of surface topographic assessments under dynamic conditions [87, 90]. Posture is also determined by the position of the person, for example in sitting, however rastersterography studies seem to be limited to standing images.

Rastersterography studies have shown good reliability for normal and overweight adults of static images in relation to anterio-posterior radiographs [88], and for dynamic rastersterography in comparison to ‘gold standard’ for motion analysis (Vicon), as referred by Betsch et al., [90]. Nevertheless, studies have also shown an underestimation of spinal curves in a group of adolescents with idiopathic scoliosis [89]. This generates a limitation of the applicability in groups of patients that do not have a straight “normal” spine.

Although static and dynamic rastersterography measurements enable the analysis of the spine curvature both in the coronal and the sagittal plane the pictures are only taken from a posterior view of the patient. Consequently, the changes in the sagittal plane curves are based on the interpretation of the shape from a posterior view of the participant and not from a true lateral view, which could open the possibility of misinterpretation due to cross-talking of the planes. Furthermore, the need for a clear view of the back of the person limits the applicability in the context of assessment of motor control, as in many cases such tests require a therapist to be positioned behind the patient and providing support. As far as it can be found, rastersterography measurements have being developed for use during upright standing or walking, and thus are not appropriate for assessment of patients with compromise of their lower limbs.

7. 3D Postural Analysis

7.1 3D Motion Capture Systems (Optoelectronic Systems)

Motion analysis systems (e.g. Vicon Nexus, Oxford, UK) are an essential tool for the study of posture and movement, as they permit the measurement and recording of three-dimensional (3D) human movements during sport and exercise [91] and in specialised clinical environments. 3D motion capture systems open the possibility of collecting data of individuals as they move around performing a task or activity or during prolonged static tests. This is achieved through the use of markers that, placed on anatomical landmarks, are automatically registered in space with optoelectronic cameras for later processing through specialised software [92]. The precise objective of the study will necessitate a marker set specific to that objective and the literature reports a variety of marker sets.

The most common marker configurations are designed to capture the movement of the lower limbs during walking or running [91, 92]. There are additionally some specific markers sets that have been defined for the upper limbs [93]. However, the models that have included the trunk segment have generally considered it as a single rigid segment extending from the iliac crests to the shoulders [94], or considered only the shoulder girdle [95]. This implies that the information about postural alignment of the trunk is greatly simplified.

In a clinical context, optoelectronic systems have been used to evaluate the body configuration during a prolonged static posture [95], and to determine the balance strategies, in terms of joint angles, when a perturbation occurs [96, 97]. Studies that have focussed more specifically on postural alignment in sitting include the work by Murans et al. [95]. This used the coordinates of markers to define the position of the pelvis segment and of the thorax-shoulder complex of children with cerebral palsy during a sitting trial. Similarly, Hayes et al. [97] calculated standing joint angles for the thorax, pelvis and thighs from the information obtained from the 3D motion capture system when a participant tried to maintain a horizontal position of the shoulders through a rocking movement. The focus of these studies, however, has been the postural adjustments to maintain a balanced posture and not the spatial configuration of the spine and lower limbs, which is an essential component for the assessment of posture. Additionally, these studies have not related their findings to the neuromotor control required to maintain a general balanced posture, even if not vertically aligned.

The work of Curtis et al. [98], represents a major development in the assessment of trunk posture in sitting. Their study reports the identification of several trunk segments and enables the quantification of each segment’s position in relation to the immediately proximal segment. In their work, Curtis et al. [98] measured segmental trunk and head sway of typically developing children aged 4-9 years in unsupported steady sitting. The definition of the trunk segments was based on the Segmental Assessment of Trunk Control (SATCo) [29], which subdivides the trunk into three thoracic and two lumbar segments in relation to the anatomical characteristics of the spinal vertebrae. The novelty of this work opens up the potential of measuring the kinematics of the trunk while acknowledging that the vertebral column has a considerable range of movement as a whole resulting from the combination of all the relatively small movements between two adjacent vertebrae.

Although optoelectronic systems are considered the gold standard for human movement analysis, there are several constraints limiting their use in physiotherapy environments. These include the high costs of the equipment, the need for a rigid equipment calibration, and the extensive data collection procedures which are especially limiting with young children. 3D motion capture systems have, however, an important role in the generation of new methods to study posture and trunk movement and head and trunk control and for the validation of clinical tools.

7.2 Magnetic Tracking

Kinematic information has been recorded in different studies through the use of magnetic tracking devices (e.g. Flock of Birds miniBIRD electromagnetic tracking sensors - Ascension Technology, Burlington, VT). In general, a magnetic sensor is attached to the segment of interest, while a secondary sensor provides a spatial reference. Magnetic sensors have been used to define the postural orientation and stability of a segment either by evaluating the general movements in space [99] or the angular displacement in relation to the line of gravity [56, 100, 101].

Saavedra et al. [101], Saavedra et al. [56] and Saavedra and Woollacott [102] analysed the data from a sensor attached to the spinous processes of the 7th cervical vertebra (C7) to document trunk alignment, thus assessing postural orientation and stability of the C7 sensor in relation to a vertical line located at the centre of the base of support. However, although providing useful information, this type of analysis tends to oversimplify and gives no information on the relative alignment of the trunk segments.

A different use of magnetic sensors is describe by Claus et al. [60]. In this study, 3D magnetic sensors were attached to the skin of the back to calculate sagittal spinal curves and to examine whether participants could imitate a clinically 'ideal' spinal curve at thoraco-lumbar and lumbar regions. The 3D position of each sensor was used to derive the relative sagittal-plane positions and this was used to define angles that represented different segments of the spine. The main findings of this study showed that the 'ideal' lordosed posture for the lumbar spine is derived from postures with the hip in an extended position, which makes it difficult to acquire in sitting on a flat surface. The authors also commented how, despite the fact that magnetic sensor measures accurately represented changes in lumbar flexion/extension, these measures may show smaller angles of lordosis than those made in spinal images. Claus et al. [60] did not give a reason for this problem, but it could be presumed that the differences between the measures are defined by the position of the landmarks (vertebral bodies or spinous processes) and the different methods for quantification of the spinal curvatures.

Although the literature describes the use of magnetic tracking sensors for the measurement of trunk balance and alignment as reflected by the general position of a segment in relation to an external reference, or to an adjacent segment, magnetic tracking sensors have been little used for the specific assessment of postural alignment. Magnetic sensors would appear to have great potential for the assessment of motor control. However, the fundamental studies to calculate spinal curves in groups with different ages and in the presence of pathologies remains to be done and the applicability in a physiotherapy clinical practice is yet to be determined.

8. Force Platform

A force platform is a device designed to measure contact forces. They are usually located in the ground due to the importance of foot-ground interaction in biomechanics and gait, but can also be mounted within other apparatus e.g. to measure seated forces. Force platforms using transducers are based on the principle of Newton's third law of motion[25] and can typically measure six variables[26] [103, 104].

Force platforms have been used to perform posturographic assessment in standing [105, 106], in sitting [106-109], and in kneeling [106], as well as to study the weight bearing distribution in different participant groups and positions [95, 106].

Posturographic assessments are based on the analysis of the centre of pressure[27] (COP), which enables an understanding of specific components of postural control, but does not necessarily reflect the specific body configuration a person is adopting to maintain a stable position. Variations of the COP within the base of support and the weight bearing distribution can also be a manifestation of changes in posture [106], but to understand the specific body configuration, force platforms should be combined with a kinematic measurement which can include the use of radiographs [68, 69] or 3D motion capture systems [95].

Posturographic assessments provide an objective reflection of the static balance of a person; nevertheless, it requires that the patient remains still for long periods of time (30-60 seconds) which is not always possible to achieve with young

[25] Newton's third law of motion implies that, when a force is applied to the plate each of the under-surface transducers experience a deformation that is proportional to the magnitude of the force, generating a change in voltage which is transmitted to an amplifier and then to a computer. Commercial force platforms have a rectangular shape and a variable size; they are mounted in rigid supports and generally use either strain gauged or piezo-electric transducers.

[26] Three (ground) reaction forces around the co-ordinate axes (vertical, anteroposterior and mediolateral), two co-ordinates which identify the point of force application or centre of pressure, and one friction torque about the vertical axis [103, 104].

[27] The centre of pressure (COP) represents the position of the resultant reaction force vector in relation to a plane parallel to the surface of the plate [103]. The COP has been analysed considering several variables which reflect different components of the postural control. The COP sway area, or the path length demonstrates the performance during a task; the COP velocity shows the activity and the COP displacement (anteroposterior-AP, and mediolateral-ML) can be used to understand separately the deficiencies intervening in the anterior and posterior muscles, from those involving the lateral trunk muscular groups [107].

children and often represents a challenge in children with deficits of maintaining upright control. Furthermore, the complete base of support of the patient has to be within the limits of the force platform all the time; this means that the feet while standing (plus the walking aids they might require to stand), or the bottom, thighs and feet while sitting, cannot be supported outside the edges of the platform. This can represent a problem since one of the natural strategies to enhance balance is increasing the area of the base of support.

9. Electromyography

Electromyograms (EMGs) are recordings of electromyographical signals that emanate from muscle fibres prior to their contraction. These can be detected using electrodes placed either inside the muscle (fine-wire electrodes) or on the surface of the skin overlying the muscle (surface electrodes) [110].

A primary reason for processing basic EMGs is to derive a relationship between it and some measure of muscle function [111]. EMG allows analysis of the patterns and timing of activation during quiet standing [96] or during the performance of a specific task [105, 112], and also the development of patterns of coactivation/inhibition of antagonist muscles during the acquisition of a motor ability [56, 81]. In most of these cases, surface EMGs have been complementary to a variety of kinematic and kinetic methods used in biomechanical analysis of postural control in anti-gravitational positions.

Upright balance, in standing or in sitting, requires having learnt to adjust the active stiffness of the muscles to create adequate torque to counteract the destabilizing effect of gravity [56, 96]. EMGs have been used to understand how the alterations in muscle performance can result in an increase of difficulty for completing a task, in inadequate execution of an action, or a lack of control to maintain a balanced upright posture for performing daily functional activities. This information can be of great value in interpretation of postural alignment but, on its own, EMG cannot generate an accurate image of the patient's posture.

10. Conclusion

Several studies have quantified posture in order to make the test objective and repeatable. These studies cover a wide range of technologies. They represent a step forward in the assessment of posture by moving towards a concise and specific definition of quantitative alignment. However, various limitations render most of these methods unsuitable for application in a clinical setting. Many of the technologies, for example, require complex procedures for data collection, and the need for expensive equipment, which will reduce the opportunity for use in a regular physiotherapy clinic. There is, therefore, a need to develop an objective measurement tool based on a 'clinically-friendly' system. Furthermore, most of these studies have not demonstrated the applicability of the methods with young children or patients with neurodisability; few of the technologies discussed are suitable for use with all patient groups, especially young children with poor postural control.

Those methods that do have potential in clinical environments, e.g. video and Dartfish, have not yet been used to measure postural alignment, to generate a quantitative method for assessment of posture, or in the assessment of motor control. However, these methods provide a means for development of an objective clinical assessment method, based on a quantitative model representing the 'ideal posture' in both sitting and standing. Additionally, such methods have potential for use with all patient groups as they are minimally disruptive both for the patient and for the clinician.

Table IV-1Summary table.

Method	Strengths	Weaknesses	Key References
Clinical Assessment	• Is easy to apply in all groups of patients. • Requires only very basic instruments.	• It is based on general terms that allow a wide range of interpretation. • It has shown poor reliability. • There is little information about assessments in sitting.	• Fedork, C. et al. (2003) [64] • Iunes, D. et al. (2009) [65]
Radiographs	• Allow measurements to be taken. • Can be used to describe, quantify and classify sagittal alignment of the spine. • Have been used to validate a non-invasive anthropometric approach.	• Posture analysis is generally a secondary consideration. • Radiographs imply radiation exposure. • Are complex and costly for use in a routine assessment in a clinical physiotherapy setting. • Are inadequate to assess motor control as they represent a single static image.	• Lafage, V. et al. (2008) [68] • Leroux M. et al. (2000) [71] • Roussouly, P. et al. (2005) [67] • Vaz, G. et al. (2002) [69] • Vrotec, T. et al. (2009) [70]
Photograph	• Has been used previously to give angular measurements, allowing the quantification of posture. • Can be used with the participant in standing or in sitting. • Requires low cost equipment and minimal preparation and disruption to the participant.	• There is no standardised definition of the angles that can be measured. • Results can be influenced by removing-replacing or markers. • It is a static image which captures the position of the body at a specific instant.	• Alm, M. et al. (2003) [77] • Dunk, NM. et al. (2004) [75] • Dunk, NM. et al. (2005) [76] • Iunes, D. et al. (2009) [65] • McEvoy, M. and Grimmer, K. (2005) [74]
Videos	• Allow recording of movement without any interferences with the individual. • Have the potential to generate a quantitative measure. • There are analytical tools (such as Dartfish) that can be used for the quantification of videos.	• In clinical contexts they have been mainly restricted to the provision of complementary qualitative information. • There is little information that shows the use of videos in relation to posture and alignment in standing or sitting, or in the assessment of control.	• Boxum, AG. et al. (2014) [81] • Philippi, H. et al. (2014) [82] • Saether, R. et al. (2011) [83] • Khadilkar, L. et al. (2014) [84] • Womersley, L. et al. (2006) [85]

Table IV-1Summary table (continuation).

Method	Strengths	Weaknesses	Key References
Rastersterography	• Provide a fast and radiation free image of the spine position. • Can be used under static or dynamic conditions.	• Is mainly used in static postures. • Studies appear to be limited to images in the standing position. • It takes images only from a posterior view of the patient. • Requires a clear view of the back of the person.	• Betsch M. et al. (2011) [87] • Betsch M. et al. (2013) [90] • Frerich, JM. et al. (2012) [89] • Knott, P. et al. (2010) [86] • Mohokum, M. et al. (2010) [88]
3D motion Capture System	• Permits the measurement and recording of 3D movements. • 3D systems have been used to evaluate posture configurations during prolonged static postures. • A multisegmental trunk model has been used previously. • Have an important role in the generation and validation of new methods to study posture and movement.	• Requires markers to be attached to the participant to reconstruct the different body segments. • Marker sets usually consider the trunk as a rigid segment. • Studies have not focussed on the specific configuration of the spine and lower limbs, but only on the postural adjustments. • They require high cost equipment, rigid calibration, and extensive data collection, which limit the use in physiotherapy environments.	• Burtner, PA. et al. (1999) [96] • Curtis, D. et al. (2015) [98] • Hayes, SC. et al. (2007) [113] • Murans, G. et al. (2011) [114]
Magnetic Tracking	• Has been used to define the postural orientation and stability of a segment. • Has been used to calculate sagittal spinal curves.	• Tends to oversimplify the analysis giving no information on the relative alignment of trunk segments.	• Claus A. et al. (2009) [60] • Rachwani, J. et al. (2013) [99] • Barela, JA. et al. (2011) [100] • Saavedra, S. et al. (2010) [101] • Saavedra, S. et al. (2012) [56]

Table IV-1Summary table (continuation).

Method	Strengths	Weaknesses	Key References
Force Platform	• Posturographic assessments have been done in standing, sitting, and kneeling. • Provide an objective reflection of the static balance of a person.	• Posturographic analysis is based on the COP, which does not necessarily reflect the specific body configuration of a person. • It requires a person to remain still for long periods of time (30-60 seconds) which is not always possible with young children	• Genthon, N. et al. (2007) [107] • Girolami, GL. et al. (2011) [105] • Perlmutter, S. et al. (2010) [115] • Szopa, A. et al. (2015) [106] • Van Nes, IJ. et al. (2008) [116]
Electromyography	• Allows analysis of the patterns and timing of muscle activation during quiet standing and during a specific task.	• EMG itself cannot generate an accurate image of a person's posture.	• Bigongiari, A. et al. (2011) [112] • Burtner, PA. et al. (1999) [96] • Girolami, GL. et al. (2011) [105]

V. Open and Closed Controlled Kinetic Chains

1. Introduction

Imagine you are sitting at your desk, working on your computer. Your eyes are fixed on the screen and you are deep in thought. Your hands rest on the desk. Maintaining your gaze, you reach towards your cup of coffee with your right hand, sitting upright moving away from the seat back to do so. At the same time, your left arm is lifted towards your head – but does not touch it. Your gaze on the screen is uninterrupted. This is a routine everyday postural activity but it is a very complex task of neuromuscular control. It is a combination of active neuromuscular control of an upright aligned posture while keeping the arms and trunk free of support. This chapter will explore some aspects of this control and introduce the concept of Controlled Kinetic Chains.

2. Definition

Control, as it was introduced in Chapter 'Cerebral Palsy'[28], is "the ability to regulate or direct the mechanisms essential to movement" [19] and reflects the competence of the central nervous system to coordinate the movements of individual joints and muscles based on sensory feedback. This coordinated interaction between systems will allow a person to perform everyday tasks, such as kneeling to put an object into a low cupboard, or more extreme activities such as walking on a tightrope.

Sitting is a common posture that requires neuromuscular coordination and is fundamental to daily activities. The acquisition of independent sitting with full neuromuscular control is a milestone of typical development that is gained at around 8 months, and is demonstrated in the ability a child has to maintain quiet sitting without trunk support and with hands free [6]. This enables bilateral hand

28 See Chapter II, under Motor Control Definition and Assessment (Section 4).

function and thus is vital to learning and development [6]. Aligned independent sitting, as previously discussed[29], requires the child to have developed vertical head and trunk control, which is characterised by the spatial relation of these segments to each other and to the base of support. Furthermore, ‘controlled independent sitting’ implies having the ability to maintain the posture statically (Static control), during active movement (anticipatory or Active control) and to restore it after a perturbation (compensatory or Reactive control).

In the presence of a neuromotor disability, such as cerebral palsy (CP), acquisition of independent sitting can be compromised leading to further functional limitations. The motor control of children with CP is most usually assessed in a physiotherapy practice through comparison with typically developing children and inferring control status from functional activities. Clinical tests such as the Gross Motor Function Measure (GMFM) and the Chailey Levels of Ability subjectively assess motor function from the variety of activities a child with CP can accomplish in relation to the motor development and functional abilities of a healthy child [18, 20]. Complementary, specific tests such as the Trunk Control Measurement Scale (TCMS) [25] and Sitting Assessment for Children with Neuromotor Dysfunction (SACND) [26] subjectively assess postural control through a variety of tasks in sitting[30].

Where the equipment is clinically available or in a research context, motor control can be assessed through the kinetic analysis of the forces contributing to movement [107], three-dimensional (3D) kinematic analysis of the body movement [98], or electromyography for measuring the activity of muscles [56]. However, the use of these methods is not practical in a clinical setting, as they need expensive equipment and are not always suitable with all patient groups, especially with young children.

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[29] See Chapter IV, Assessment Methods of Postural Alignment.
[30] Refer to Chapter II for more details about these tests.

3. Controlled Kinetic Chains

While reading these lines, notice just for a second or two how you are sitting. Is the chair you are seated on providing a firm support along your entire back? Are your arms resting on something while holding this thesis? Now, imagine you are seated on a stool with nothing around you to support yourself on and reflect upon how this feels. How much effort do you need in each of these two situations to maintain the sitting position? The amount of neuromuscular control varies in each of these scenarios; even while sitting on a stool, with an aligned posture, having one hand placed down without much weigh on it, will make a change in the control required to maintain the position.

The head and trunk are a kinetic chain of segments that must be under active neuromuscular control to attain and maintain an independent sitting posture. The term "kinetic chain", originally adopted from engineering[31], refers to a sequence of rigid segments connected by joints where forces exert control over the geometry of the assembly [28]. The joints may be pin, slider or temporary in nature. A sequence of segments and joints which connect to themselves is always described as "closed" (Figure V-1 A). When there are one or more free ends, the chain is described as "open" (Figure V-1 B and C). If both free ends of an open kinetic chain then each contact a further support surface, this will result in a "closed" chain (Figure V-1 D). A kinetic chain may also consist of both "open" and "closed" components (Figure V-1 E). When analysing neuromuscular control status, the assessor must first identify any closed sections within a specified kinetic chain: the remaining sections of that kinetic chain will then be confirmed as open chains under full neuromuscular control. Neuromuscular control may exist in some, or all, joints of a controlled closed kinetic chain but determining which joints is difficult using only visual inspection. However, by definition, all joints of a controlled open kinetic chain are under full neuromuscular control in order that the particular geometry of that open chain is maintained [28].

The head and trunk are a kinetic chain of segments comprising the head and neck and successive trunk segments to the pelvis. These axial segments branch

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[31] This was discussed by Franz Reuleaux (1829-1905) with an English translation by Kennedy in 1963. Reuleaux proposed the concept of the 'closed kinetic chain' but did not discuss any aspects of control of that chain [117].

into the upper limbs. Maintenance of a sitting posture can be accomplished using passive or using active neuromuscular control or a combination of the two. This distinction between passive and active control in functional activity has been developed by Butler and Major [28]. They used the terms “Closed Controlled Kinetic Chain” (Closed-CKC, combined active and passive control or pure passive control) and “Open Controlled Kinetic Chain” (Open-CKC, assured active control only).

In sitting, passive control can be attained by invoking internal support, generally using the anatomical characteristics of a joint of the trunk; the joint(s) are taken to end range when the ligaments then act as passive stabilizers. This is seen clearly in sitting with a lumbar collapse when the posterior ligaments provide the passive control. The presence of an internally Closed-CKC can be inferred through the observation of posture; for example, a lumbar collapse in sitting can be seen through the roundness of the lower back. Consequently, an aligned vertical posture of the head and trunk confirms the absence of internal support. Another example of passive control is to have external support when one or more segments are in contact with a surrounding surface or with any part of the own participant’s body (externally Closed-CKC). Examples are leaning against a back rest, placing a hand on the seat or thigh, holding the arms and hands on the chest, or linking the hands together even in the air. All of these actions can provide an element of cross-bracing and potentially reduce the active control needed to maintain the posture, even if the contact with the surface is a ‘light touch’. Some active control will be exerted but this could be from the arms and not necessarily within the joints of the spine as is essential for active trunk control.

Thus, for the assessor to be able to confirm full active neuromuscular control of head and trunk posture in sitting, the demonstration of both an aligned vertical posture and the absence of any external support other than the primary support surface is required. This combination is an Open Controlled Kinetic Chain (Open-CKC) where assured active neuromuscular control is responsible for maintenance of the posture.

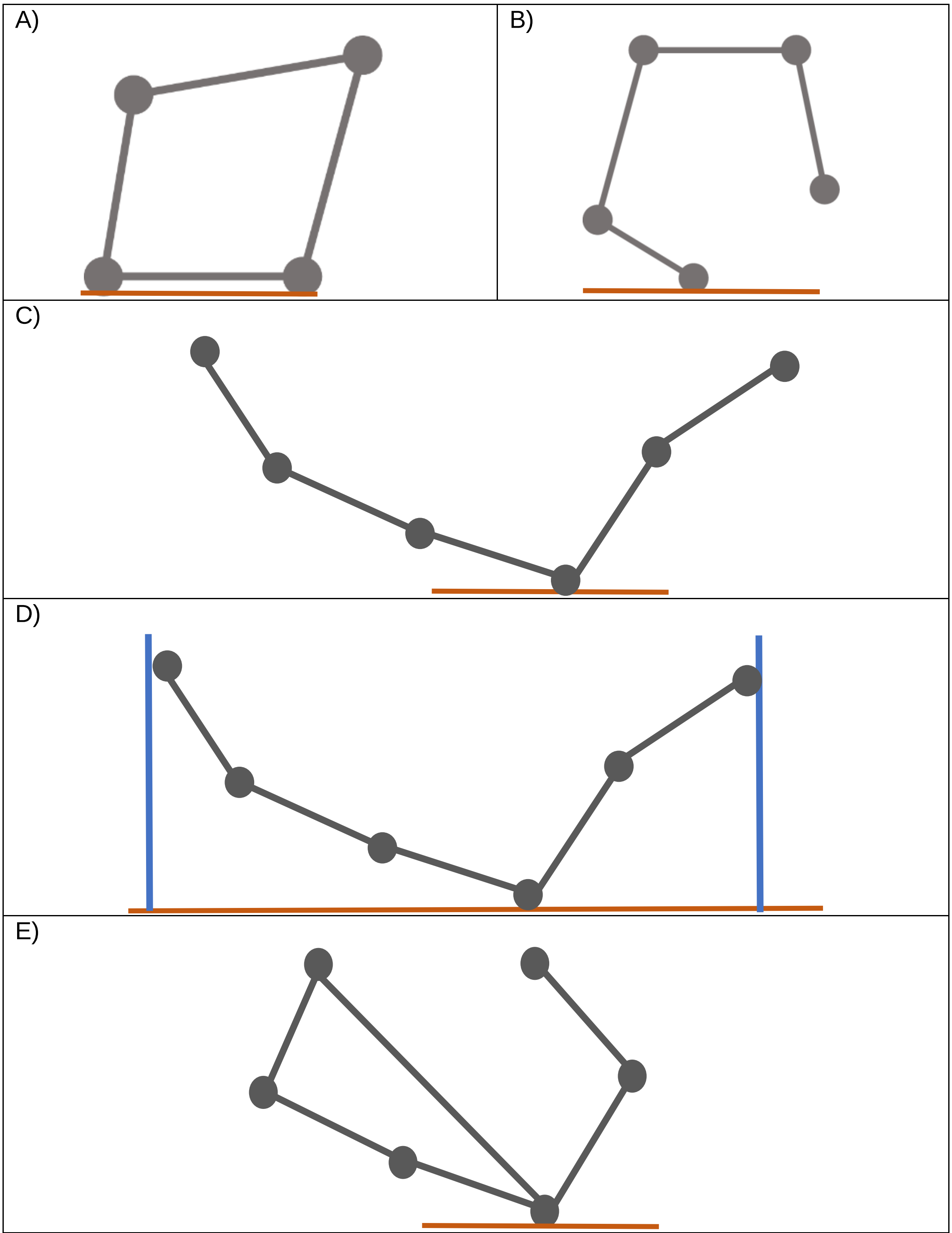

Figure V-1 Types of kinetic chains.

Lines represent segments and dots represent joints between segments. A) Closed chain; B) Open chain with only one end free; C) Open chain (as is B) with two free ends; D) Same segment and joint configuration as C but now Closed chain since there is contact by both previously free ends with an external structure arising from each end of the primary support surface; E) Part open and part closed chain.

4. Controlled Kinetic Chains and Cerebral Palsy

As a consequence of the inefficient and uncoordinated motor patterns that result from the brain injury, children with CP adopt alternative strategies to maintain a sitting position and be able to interact with their environment.

Several validated therapeutic assessments of postural control exist with testing generally conducted with the patient sitting on a flat surface. The assessments of control, previously introduced in Chapter II, do not always consider fully aligned head and trunk posture and the use of the arms and hands as compensatory strategies when testing for control, i.e. these assessments will not generate a complete picture of the active neuromuscular control status. For example, the SACND [26] requires that one hand is on the lap during the dynamic module and lacks consideration of trunk alignment. Although the GMFM [18] and the TCMS [25] require arms and hands free of support to score a child as able to maintain ‘upright’ bench sitting, they do not include assessment of fine trunk adjustments such as subtle collapse. Control is thus assessed only through Closed-CKC tasks either by supporting with the hands and arms, or by leaving open the option to take joints to end range.

In contrast, the Segmental Assessment of Trunk Control (SATCo) [29] considers the alignment of the head and trunk in conjunction with an absence of external support (light of firm) from the hands and arms, or the seat back. Fulfilment of these requirements enables positive identification of active control. The SATCo assesses Static, Active and Reactive control at six discrete trunk segmental levels in addition to full trunk control and this requirement of aligned posture combined with an absence of external support applies to all three test elements (Static, Active, Reactive)[32]. Figure V-2 to V-4 illustrate these concepts of strategies that compensate for the lack of full active control. Figure V-2 shows an example of passive control, where the hands on the bench are providing external support and the trunk is in lumbar collapse. In Figure V-3 the hands of the child are in the air; however, the trunk, again, is in lumbar collapse. The third example of a Closed-CKC is presented in Figure V-5 where the child has an aligned posture of the head and trunk, but the hands are in contact with the bench. Active

[32] A detailed description of the SATCo is included in the Appendix A.

control can only be credited when the child has his trunk, hands and arms free of support and an aligned head and trunk posture (Figure V-4), which represents an Open-CKC.

Clinical assessment of control deficit is essential for development of an accurate therapeutic plan. Assessments typically test the child's control under unbalancing situations without consideration of the adjustments the child does to maintain a balanced position (for example arching the back, or supporting him/herself with the hands). However, identification of the internal and external control strategies adopted by children with CP is essential to provide appropriate therapeutic support while encouraging the use of active control. Otherwise, a child may be offered too little support, necessitating the use of compensatory strategies to maintain a posture, or too much support when control learning is not challenged. Furthermore, adequate support during therapy or everyday activities combined with the active stimulus to maintain an aligned vertical posture can help to modulate secondary musculoskeletal problems, while improving the acquisition of functional skills.

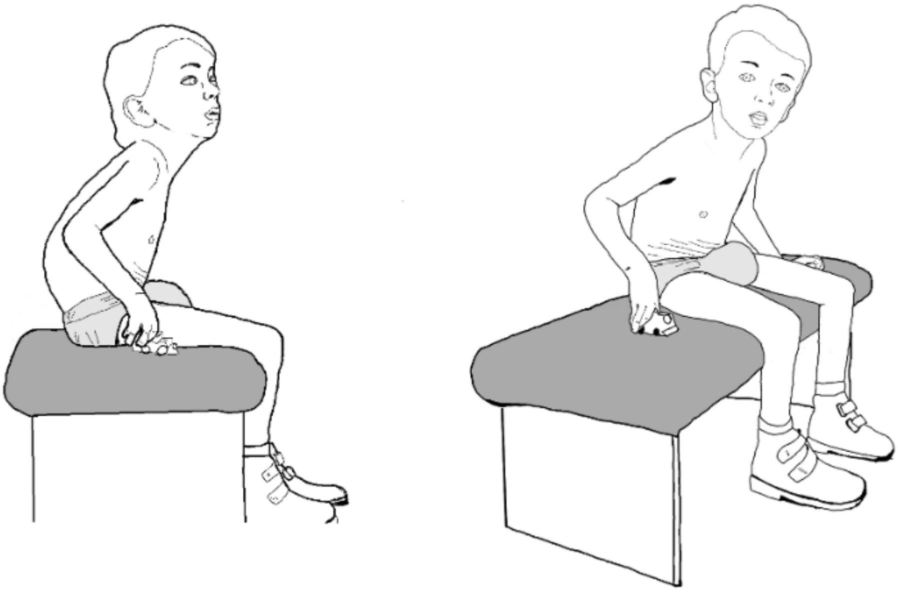

Figure V-2 Strategies to compensate for a lack of active neuromuscular control.

Diagram of a lateral and an oblique view of a child with the back rounded and the hands down while maintaining a sitting position Closed-CKC by a) taking spinal joints to end range and b) hand support.

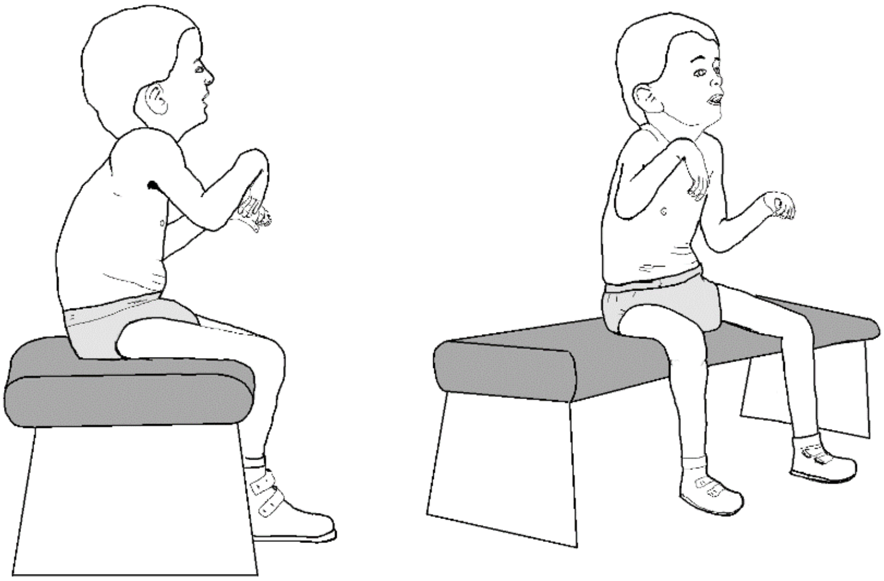

Figure V-3 Strategies to compensate for a lack of active neuromuscular control.

Diagram of a lateral and an oblique view of a child with the arms free in the air but a rounded trunk. This remains a Closed-CKC since the spinal joints are still at end range and so active control is not demonstrated.

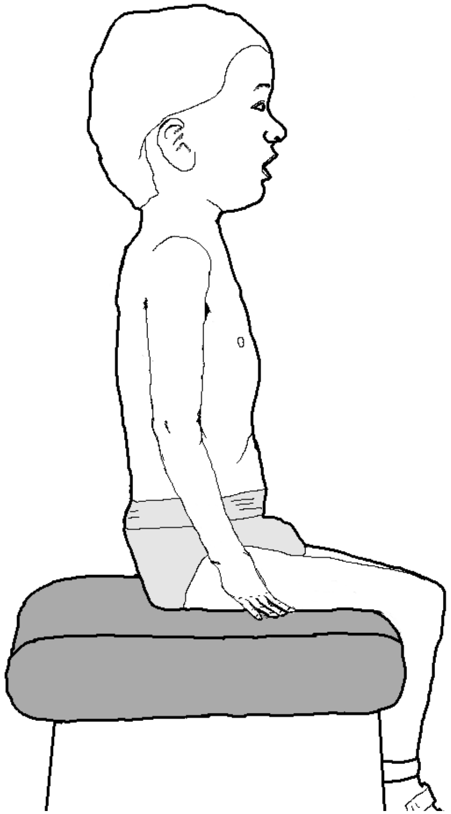

Figure V-5 Strategies to compensate for a lack of active neuromuscular control.

Diagram of a lateral view of a child showing an aligned trunk posture but while propping with his hands on the bench. Active control cannot be credited as it remains a Closed-CKC.

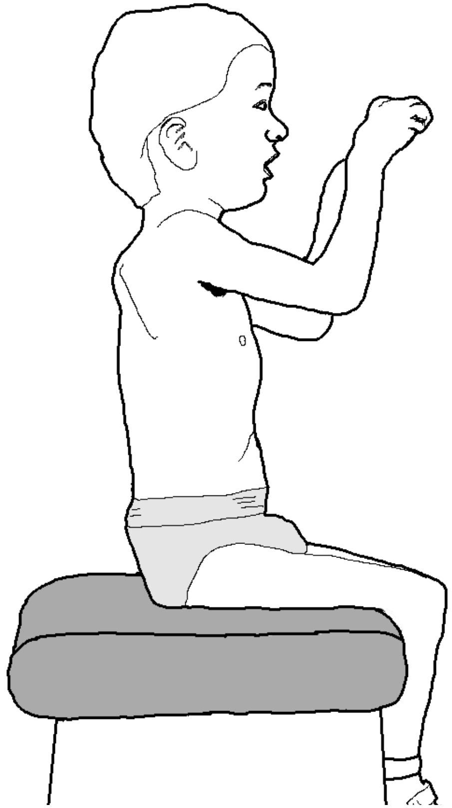

Figure V-4 Demonstration of active neuromuscular control.

Diagram of a lateral view of a child an aligned head and trunk posture and with the trunk, hands and arms free of support.

5. Quantification of Controlled Kinetic Chains

Although detailed, all the clinical tests are based on a subjective assessment and mainly evaluate the responses under unbalancing situations, with no direct reference to the control strategies that are used. Only the SATCo considers both the internal and the external strategies a child uses in compensation in order to correctly identify the level of control demonstrated; however, it remains an observational test.

Objective quantification of CKC is desirable because it is repeatable and eliminates the sources of variability between and within assessors. Furthermore, it has the potential for complementing clinical assessments and quantifying changes over time.

The position of the hands and arms in relation to independent sitting has been studied before both using video analysis [118] and a 3D motion capture system [119]. These analyses were related to symmetrical or asymmetrical reaching and to the quality of reaching and manipulation. 3D motion capture systems also have been used to describe quiet sitting in children with spinal deformities [114] and to measure posture and sway of the head and trunk in typically developing children [98]; however, these studies did not consider the use of the hands and arms as a strategy to maintain the sitting posture.

As far as could be determined from the literature, the use of the upper limbs to compensate for poor trunk control in sitting has only been identified in relation to the SATCo [29], and there are no quantitative studies that have analysed the interaction between internal and external control strategies.

6. Conclusion

The presence of active neuromuscular control of the sitting posture can only be credited if there is an Open-CKC of the trunk and upper limbs. Therapeutic assessments of control generally tend to ignore the identification of the strategies used by a child with a neuromotor disability to maintain a balanced sitting position. Only the SATCo associates the demonstration of an Open-CKC with the presence of active neuromuscular control in sitting. This approach favours the development of an accurate therapeutic plan. However, this assessment remains a subjective test.

The quantification of both components of support (internal and external) serves to provide an objective assessment of the segmental level of trunk control for children with CP. The identification of the internal support can be accomplished through the quantification of postural alignment in sitting, allowing a quantitative measurement of control expressed, for example, as the deviation from alignment at a specific trunk segmental level. The objective identification of the position of the trunk, hands and arms relative to each other and to external surfaces or objects serves to identify the adoption of externally Closed-CKC. The combined use of both measures would provide the means to measure change after a therapeutic intervention.

Quantification methods, however, will need to be based on technologies that can be routinely found in a clinical setting and can be applicable to a wide range of patient groups and pathologies, including young children and those less able to actively co-operate.

Objective

VI. Objective

The concepts presented in the Literature Review revealed i) the importance of generating an objective assessment method of head-trunk control in sitting and ii) that this method should consider both components of control, i.e. alignment of the head and trunk and the identification of the position of the trunk, hands and arms relative to each other and to external surfaces.

Additional pertinent points arising from the Literature Review and relevant to forming the Objective are:

- The most common physiotherapy assessments of children with cerebral palsy (CP) do not consider the two separate components of control. It is thus likely that these assessment outcomes will not show a complete representation of a child's control status. Only the Segmental Assessment of Trunk Control (SATCo) [29] considers both components of control when generating a clinical judgement of the segmental level of trunk control.
- Having an accurate picture of the control status of a child is essential for the definition of the best suitable therapeutic intervention for the child, and for the further validation of therapeutic interventions which will help to standardise intervention protocols.
- There are many different methods that could be used for the objective assessment of head and trunk control; however, very few of them could potentially be used in a routine physiotherapy practice. Although those methods whose characteristics makes them more 'clinically-friendly', such as video recordings, have not previously been used in the quantitative assessment of postural control in sitting, their potential justifies their use in this project.

The main Objective of this project was, thus, to develop a clinical tool for the objective measurement of head and trunk postural control in sitting for children with cerebral palsy. Three main studies aims were defined to achieve this objective: i) to develop and validate a clinically appropriate method to quantify seated postural alignment of the head and trunk; ii) to develop and validate a clinically appropriate method to identify (classify) and quantify the presence of open controlled kinetic chains in a seated posture: and iii) to validate the combined use of these quantified video based methods to determine the segmental level of Static trunk control in children with CP during a SATCo.

These three studies are reported in the Chapters: ‘Quantification of Seated Postural Alignment of the Head and Trunk’ (Chapter IX), ‘Objective Identification of the Upper Limb Component of a Controlled Sitting Posture’ (Chapter X), and ‘Quantitative Classification of the Segmental Level of Head and Trunk Control in Children with Cerebral Palsy’ (Chapter XI).

Methods

VII. Ethical Statement

This project had ethical approval obtained from the NHS Health Research Authority (NRES Committee South Central, United Kingdom) (REC: 14/SC/1182, IRAS ID: 157263) and from the Manchester Metropolitan University Ethics Committee.

The study was conducted in accordance with the Declaration of Helsinki guidelines.

VIII.Methods

1. Introduction

Identification of active neuromuscular control, as described in the literature review, requires the positive identification of postural alignment when the trunk, hands and arms are free of external support (Open Controlled Kinetic Chain, Open-CKC), where 'postural alignment' refers to the position of body segments (head, shoulders, pelvis, etc.) in relation to an 'ideally aligned posture' in a specific position, such as standing or sitting. There are different methods used in the assessment of postural alignment, which in the present project represents the internal component of a Controlled Kinetic Chain (CKC). These methods include qualitative approaches, such as clinical observation, and approaches that can provide a quantitative measure of posture such as radiographs and rastersterography. Despite many of the advantages of most of the quantitative methods in the assessment of postural alignment, there are several limitations to their application in a clinical context. These limitations range from the high cost of the equipment to the difficulties of their application with all the varied groups of patients that attend a physiotherapy practice. In contrast, qualitative assessments can generally be used with a large variety of patients, but are based on a subjective assessment[33].

In the present context, the positive identification of active neuromuscular control through the identification of the position of the hands and arms (which in the present project represent the external component of a CKC), is typically done by human observation. Some studies, however, have used kinematic analysis (3D motion capture systems, video recordings, magnetic sensors) to identify the position of the hands in relation to a specific target [56, 102, 120, 121]. Nevertheless, the position of the hands has been associated only with the stages of development of independent sitting and not with the strategies to overcome poor neuromuscular control; furthermore, the kinematic analysis has only been described from a qualitative perspective [56, 99].

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[33] Refer to Chapter IV, Assessment Methods of Postural Alignment, for a detailed description of these methods, their advantages and limitations.

In the previous chapters of the literature review, many methods were described that offer good potential for developing a quantitative assessment method for the identification of both components of a CKC. However, most of these are not suitable to the research developed in this project, as they are not appropriate for young children, or their use is not compatible with the procedures, for example requiring a clear view of the back of the participant.

This Chapter describes the methods used in this project for data collection, processing and analysis. Two different groups of participants were included in the present project: an Adult-group recruited for the first and the second studies (Chapter IX and Chapters X respectively), and two Child-groups that took part in the second (Chapters X) and third studies (Chapter XI). The specific characteristics of the groups are included in the 'Participants' section of each chapter.

A brief description of Kinect is included in the final section. Kinect initially seemed to have potential but was ultimately not used in this work; the reasons and the limitations found in initial stages of the project are given in the Kinect section.

2. Video

2.1 General Information

Videography has been used for many decades in the analysis of human motion. Modern video cameras deliver excellent picture quality and can achieve high-speed frame recording [122] which makes them ideal for sport performance analysis enabling detailed analysis of individual movement patterns. This method offers the potential for low-cost analysis, with minimal interference to the athlete, both indoors and outdoors, and allows a visual feedback to the individual [78, 122].

Video analysis of a person's technique may be qualitative or quantitative. The qualitative analysis of the movement provides feedback to the athlete. Qualitative analysis requires a detailed and systematic analysis of the individual's movement pattern by the observer. Quantitative analysis requires the digitalisation of specific landmarks to represent the objects in the recording (e.g. body segments, joint centres, equipment) which makes it a time-consuming task along a large number of video images. However, software development has facilitated this digitalisation and tracking of landmarks, favouring the kinematic analysis of a specific action. A quantitative analysis enables comparison between and within individuals, both in a cross-sectional or a longitudinal analysis [78, 122]. Quantitative analysis generated from videos has been largely used in research as a mean to generate performance indicators of interest to coaches and players [123, 124] and to understand injury mechanisms, for example non-contact anterior cruciate ligament injury [125].

Video recordings have been less commonly used in clinical research contexts than in the sport and exercise context. In clinical settings, the use of videos has been mainly restricted to providing complementary qualitative information in studies of balance and posture [81-83]. A few studies have used video-based systems to perform quantitative gait analysis [79, 80] and assessments of functional range of motion of the shoulder in relation to functional tasks [84]. Nevertheless, overall, there is little information about the clinical use of video for quantitative analysis, as previously described in Chapter IV. However, the development of analytical tools such as Dartfish (Dartfish 7, TeamPro 7.0), means that there is now much greater potential for the use of video in a clinical context to quantify and validate clinical tests and therapeutic interventions. Dartfish is a software that enables biomechanical analysis from videos [126]; it has a clear user interface that allows visual monitoring of the processing that is being performed. Although there are some limitations related to tracking and speed of movement (see Section 2.3.3, page 80), this work has taken advantage of its potential for video analysis. While there are different pieces of software available to generate a comparable analysis that the one done in this project, Dartfish was selected as it has been previously used in a similar way for other projects developed at MMU.

2.2 Technical Characteristics

2.2.1 Cameras Characteristics

Two JVC, HD Everio RX110 were used for video recordings in this project.

2.2.2 Characteristics of the Video Files:

Frame rate 25 frames per second.

Image size 1920x1080.

Type of file generated .MTS files Advance Video Coding High Definition (AVCHD).

Bit-rate of 21295 kilobits per second (kbps).

Independent .MTS files were generated by the camera each time the recording button was pressed to start until pressed to end. The camera, however, has a default setting where it would start a new file after 23 minutes 8 seconds of uninterrupted recording.

The maximum size of the files was 3.89 GB (23’ 8’’).

2.2.3 Camera Setup

Cameras were placed and maintained at a constant distance in each experimental setup; the distance between the participant and each camera was defined by the largest distance the space allowed for positioning the camera while permitting free movement behind it. For the Adult-group a camera was placed on the left side of the participant at a constant distance of 3.80m and a constant height of 0.90m and a second camera directly in front at a constant distance of 3.90m and a height of 0.90m. For all child participants, the side camera was placed on the right side of each child at a constant distance of 3.0m and a constant height of 0.75m; the second camera was placed at right diagonal front (approximately 45°) at a constant distance of 2.5m and a height of 0.75m.

Cameras were mounted on spirit-levelled tripods to ensure correct alignment of the camera with the plane of motion. A horizontal scaling reference was included for the side and the frontal planes of motion enabling image coordinates to be transformed to real world coordinates; the reference was a coloured tape attached to the floor, for the adult data collection and to the bottom side of the bench for the child data collection. For each recording session, a 'calibration' trial was taken for each view, with only the bench and the scaling reference in view. These were used to obtain a clear view of the scaling reference and to ensure a correct setup of the cameras. Calibration as described was performed following the procedures described by Payton [122]. For simultaneous recording, cameras were started manually one after the other as fast as was practically possible.

2.3 Dartfish

2.3.1 What Dartfish Is

Dartfish is a two-dimensional (2D) video analysis software that provides advanced tools for the biomechanical analysis of performance. It has typically been used to enhance training programs and improve athletic performance, both during and after workout [126]. To do this, Dartfish combines technical, tactical and statistical analysis.

Although Dartfish has been typically used in the exercise and sports context [127, 128], it has the potential to be used in a clinical setting e.g. for movement analysis and rehabilitation [84].

2.3.2 What Dartfish Does and How Dartfish Works

2D-video analysis tools of the Dartfish software enable the "biomechanical observation, comparison and quantitative measurement of time, distance, angle and position" [126]. Measurements are generated from the automatic or manual tracking of drawings added to the video. These drawings can be markers, angles or distances, depending on the purpose of the analysis.

In the case of the automatic tracking of markers (as the main outcome obtained from Dartfish in the present project), the software automatically draws the trajectory of the defined marker. For each marker a sequence of coordinates (x, y) will be generated for the length of the trial or of the selected time. Coordinates will be defined in relation to an ‘origin’ and a ‘measure reference’ (Figure VIII-1). The origin of the coordinate system can be manually defined by the user at any convenient point within the video area; the measured reference (in meters, m) has to be defined from a known distance to relate the image size to real-life distances. In the absence of these (origin and measured reference) the coordinates of a marker will be provided as the distance in pixels in relation to the top-left corner of the image. If an origin and a known distance in the plane of motion are provided, Dartfish will give the coordinates of the marker as the distance in metres (m) to the origin. This was the method used in this project.

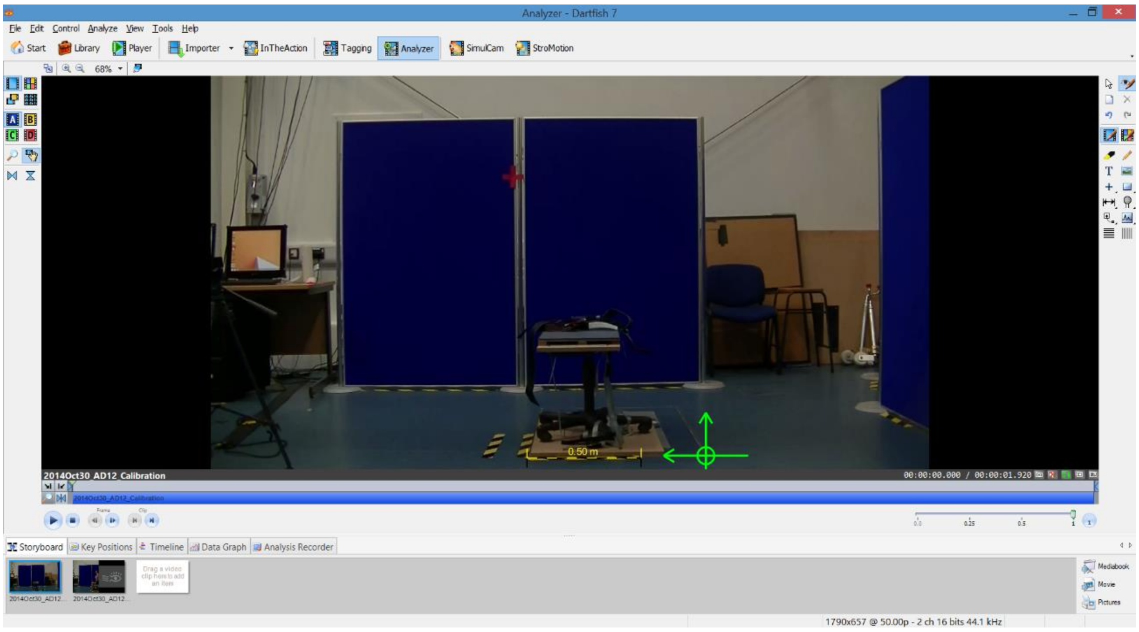

Figure VIII-1 Calibration trial, origin and measured reference for the lateral view.

Showing a representative calibration trial from the side camera. The defined origin (x horizontal positive to the left, y vertical positive up) is shown in green and the measured reference (0.50m) shown in yellow-black.

2.3.3 How Dartfish Was Used

After videos were imported to Dartfish, analysis was done using the "Analyser module". This module allows comparison and synchronisation of up to four clips, using a collection of drawing and text tools, and identification of key positions in the action.

- Synchronisation of side and front/oblique videos

Synchronisation of side and front/oblique videos was done following these steps:

i) Opening the side (A) (Figure VIII-2) and frontal/oblique (B) (Figure VIII-3) videos for the same session in the same *Storyboard*[34], using the side-to-side view.

ii) Selecting and saving a key position on video A, that was clear and distinctive (Figure VIII-4).

iii) Both videos were played simultaneously using the side-to-side view.

iv) Using the Timeline tool, video B time position was adjusted so the action matched the action in video A (Figure VIII-5).

v) Corroboration and further adjustment of the manual synchronisation was done using the merged view.

vi) On video B the equivalent key position to video A was selected and saved (Figure VIII-5).

[34] The *Storyboard* is the Dartfish file that contains the different analysis on an Analyser project [126].

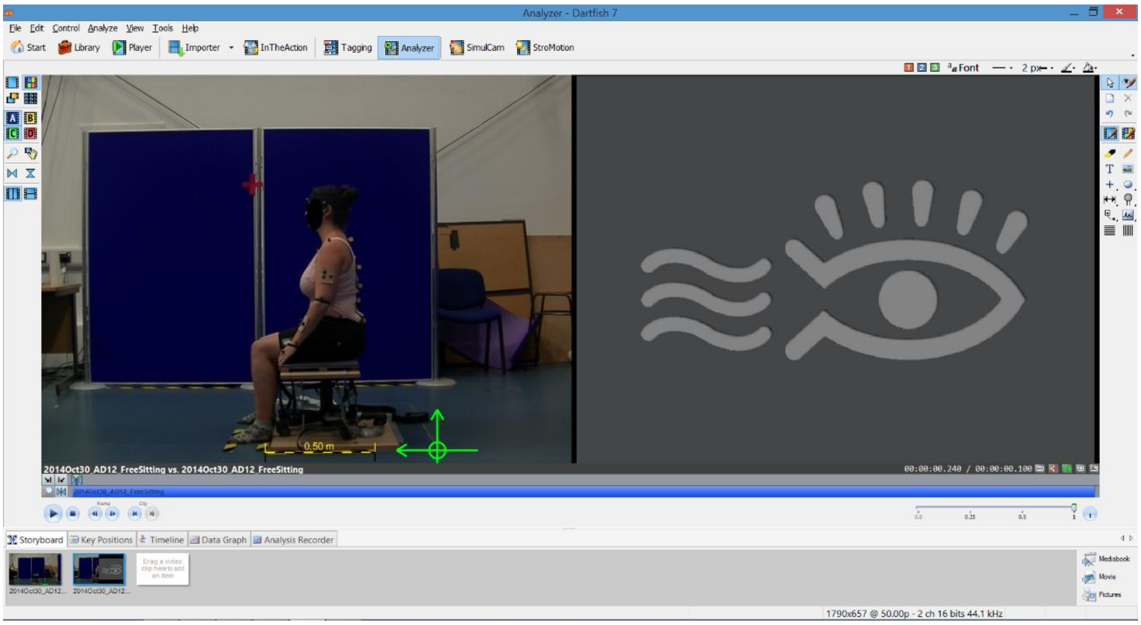

Figure VIII-2 Opening side video (video A).

Showing Dartfish view of a *Storyboard* in the Analyser module, side-to-side view. The left panel shows the side video of a trial with the origin (green) and the measured reference (yellow-black). The right panel shows the software is waiting for video B to be opened.

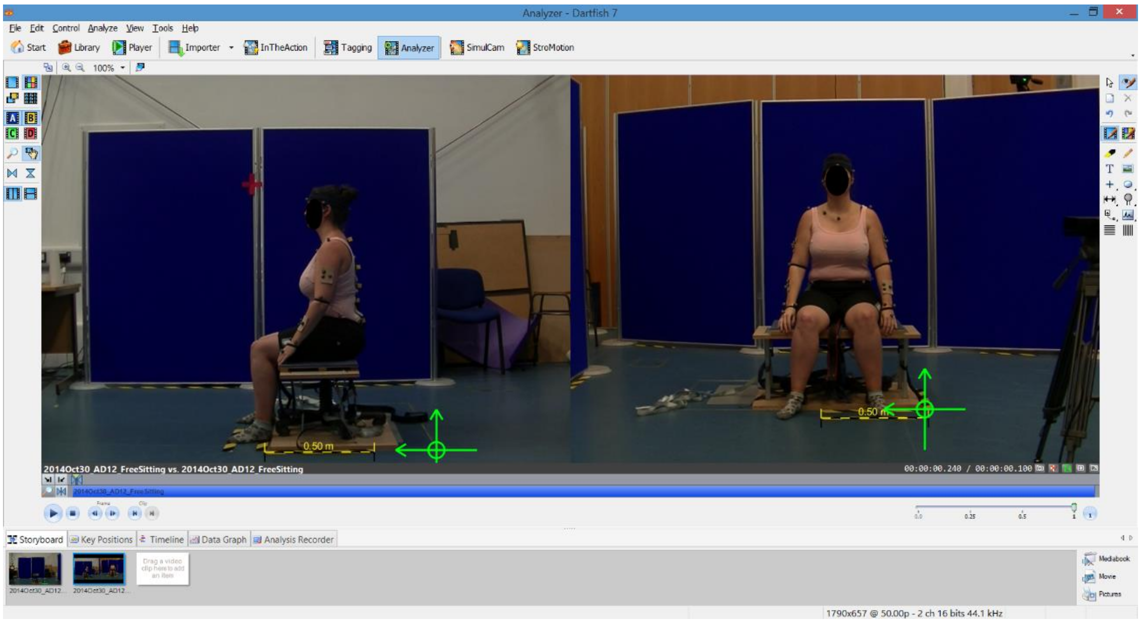

Figure VIII-3 Opening front video (video B).

The left panel shows the side view of a trial and the right panel shows the corresponding frontal view of the same trial (side-to-side view). The origin (green) and the measured reference (yellow-black) are shown in both views.

Figure VIII-4 Selection of a key position in video A.

Showing a distinctive position in video A (left), that is selected and saved as a key position (red arrows).

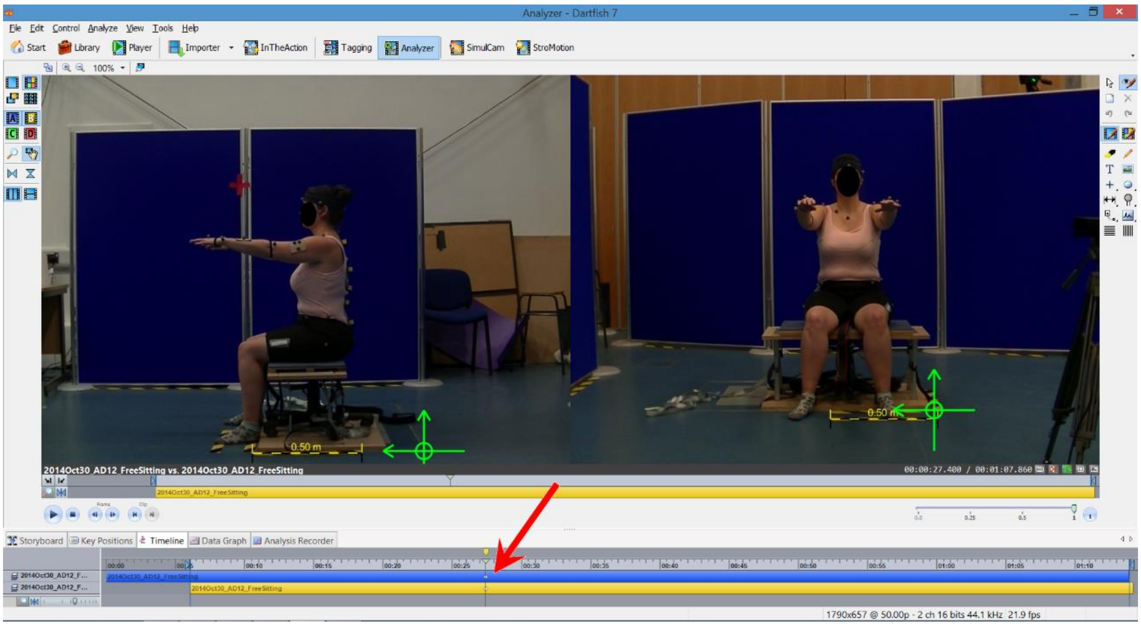

Figure VIII-5 Synchronised videos A and B and equivalent key position.

Using the Timeline tool, video B position was adjusted to make the action match with video A (red arrow).

- Video clipping

Once both videos were synchronised, the long videos were clipped using the side view videos to create individual files of each segmental level tested.

The start and end points for the segmental level clip were defined by the positioning and lifting of the assistant's hands providing trunk support. This ensured that there was no missing information for each segmental level.

Each segmental level clip was further divided into the specific trial tested (e.g. Static, Active, Reactive). Each trial formed the basic unit of analysis in the present project.

- Trial calibration

Definition of the reference distance

Using the calibration trial the horizontal measured reference was digitalised and later re-used in the movement trials (Figure VIII-1).

    - Definition of the origin and coordinate system

The origin of the coordinate system was defined at floor level in a clear landmark. The x coordinate was always horizontal, and the y coordinate was vertical. The x axis was more positive to the front of the participant, and the y axis direction was more positive towards the head (Figure VIII-1).

- Marker tracking
    - Tracking method used by Dartfish

The Dartfish automatic tracking follows the trajectory of an object. 'Object' refers to the collection of features that are around the selected marker and within the tracking area. For Dartfish to successfully track objects they must remain clear and visible.

    - How tracking was done

Tracking was done following these steps:

i) Going to the start of the clip.

ii) Selecting the marker drawing tool and identifying the object on the video (Figure VIII-6).

iii) Selecting the object speed from the menu (Figure VIII-7):

  - Slow object (search 5% of image)
  - Medium speed object (search 10% of image)
  - Fast object (search 20% of image)

iv) Defining the area around the marker to be tracked (Figure VIII-8 and Figure VIII-9)

v) Playing the trial for the automated tracking to run (Figure VIII-10).

vi) In the cases where the tracking had changed the trajectory and lost the object being tracked, the video was stopped, rewound and the marker trajectory corrected.

The speed of the object was selected in relation to the possible amount of movement an object could have: ‘Fast’ for the Head markers, ‘Medium’ for the trunk markers and ‘Slow’ for the Pelvis.

Lost trajectories were the result of objects interrupting the visibility of the tracked feature or marker such as an arm passing in front of a given marker.

The x and y coordinates of each marker were collected in a time-dependent data table (Figure VIII-11). The data collected in the data table was exported to a comma separated values (.csv) file for further processing and analysis.

The same tracking process was repeated for the frontal video (Figure VIII-12). The hand and elbow’ markers were defined as ‘Fast’ objects and coordinates of the markers and other anatomical landmarks were exported to a separate data table.

  - Which markers were tracked

For the reconstruction of the different segments from the 2D-videos, different markers and landmarks were used. Markers used for the side view analysis are presented in Table VIII-1 and for the frontal view are described in Table VIII-2.

2.4 Clips and Images for Clinical Assessment

For each trial the video-clip before tracking of both views was exported as a Windows Media Video (.wmv) file (25frames/ second, 960x540). Using a MATLAB code the clips were separated in frame-images. The consecutive frames-images were used for the clinical identification of relevant frames, i.e. frame numbers where posture was aligned used for the ‘Quantification of Seated Postural Alignment of the Head and Trunk’ (Chapter IX, ‘Alignment Study’), and the ‘Quantitative Classification of the Segmental Level of Head and Trunk Control in Children with Cerebral Palsy’ (Chapter XI, ‘Levels of Control Study’), or frame numbers where the arms and hands were unsupported as in the ‘Objective Identification of the Upper Limb Component of a Controlled Sitting Posture’ (Chapter X, ‘Upper Limb Study’).

Video clips were re-arranged in relation to the needs of each independent study.

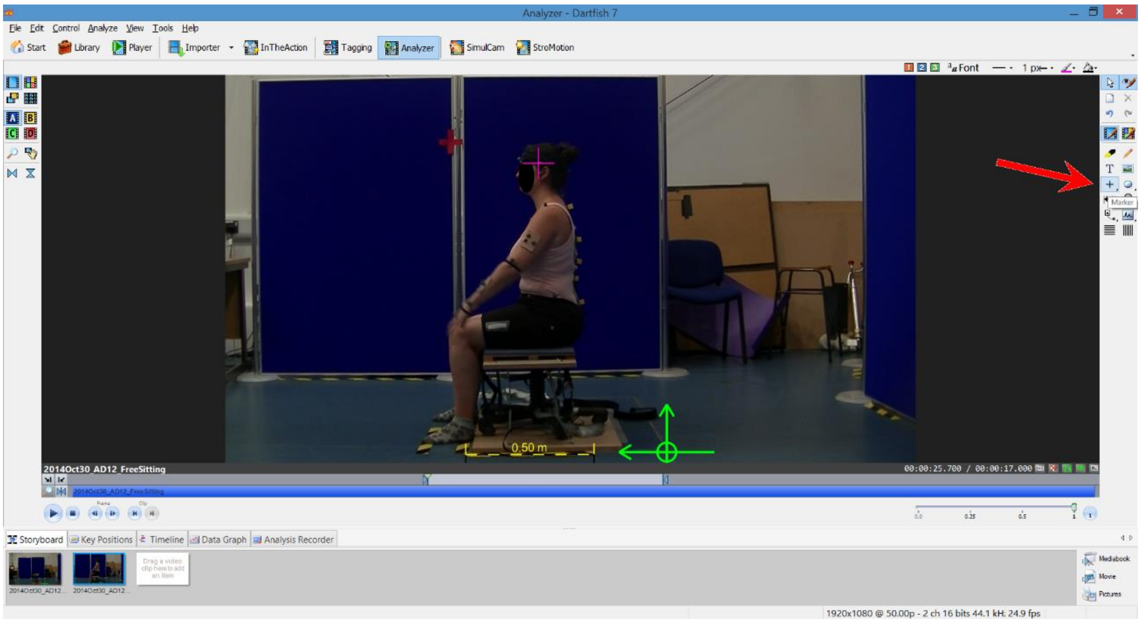

Figure VIII-6 Marker selection.

Showing where to select the marker drawing tool (red arrow) and identifying the object (Head Left marker) on the video (pink cross).

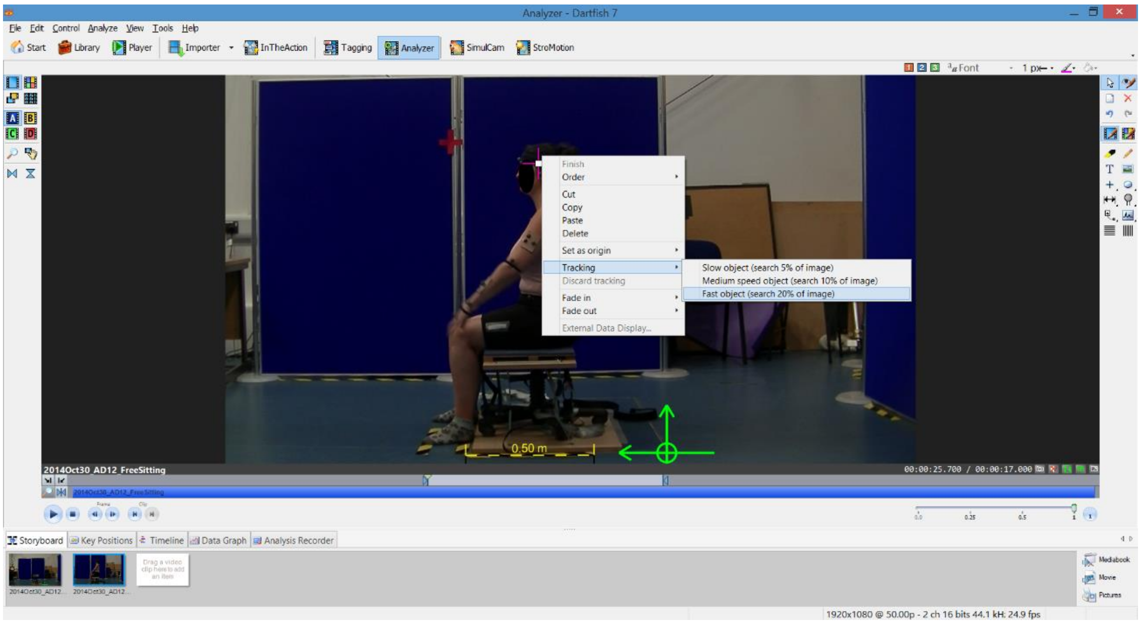

Figure VIII-7 Definition of the speed for the automatic tracking of the marker.

Showing the menu to select the object speed.

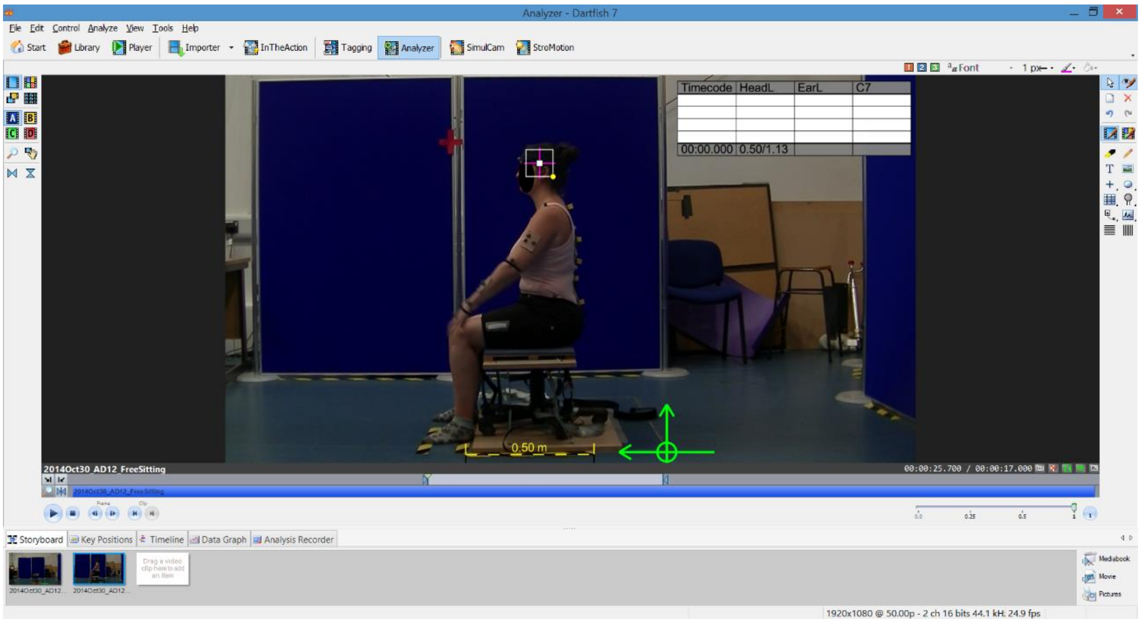

Figure VIII-8 Adjustment of the marker area to track (1).

Showing the default tracking area around the marker.

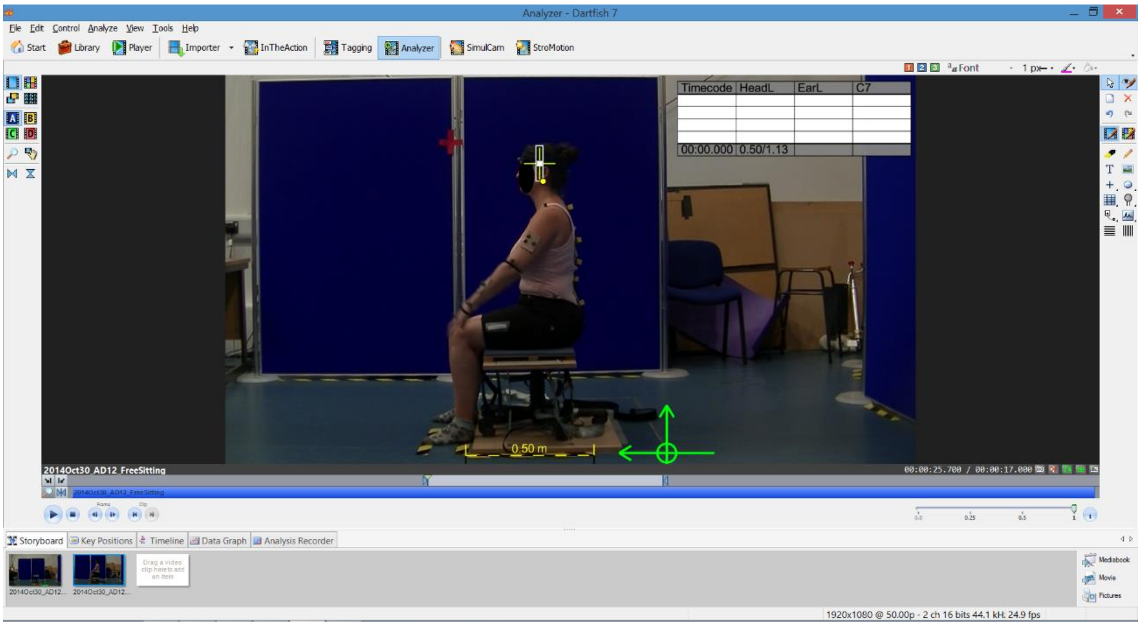

Figure VIII-9 Adjustment of the marker area to track (2).

Showing the adjusted tracking area around the marker.

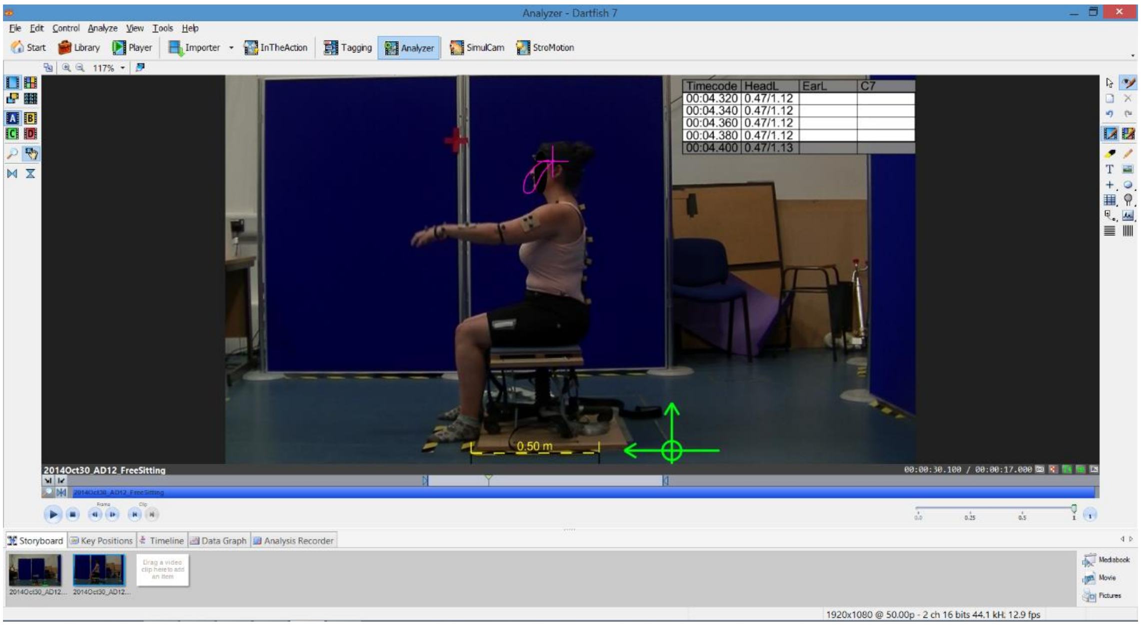

Figure VIII-10 Head marker automatic trace.

Showing the trace generated for the marker (pink line) during the head movement.

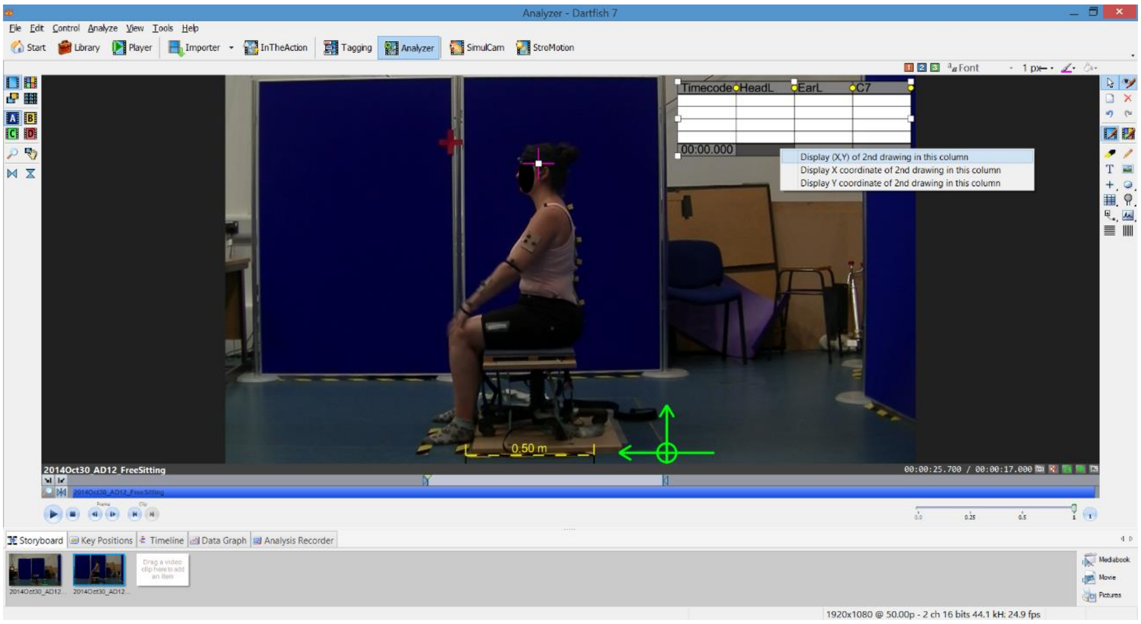

Figure VIII-11 Insertion of the x, y coordinates of the marker in the data table.

Showing the data table (top-right) where the coordinates of the marker (x, y) were collected.

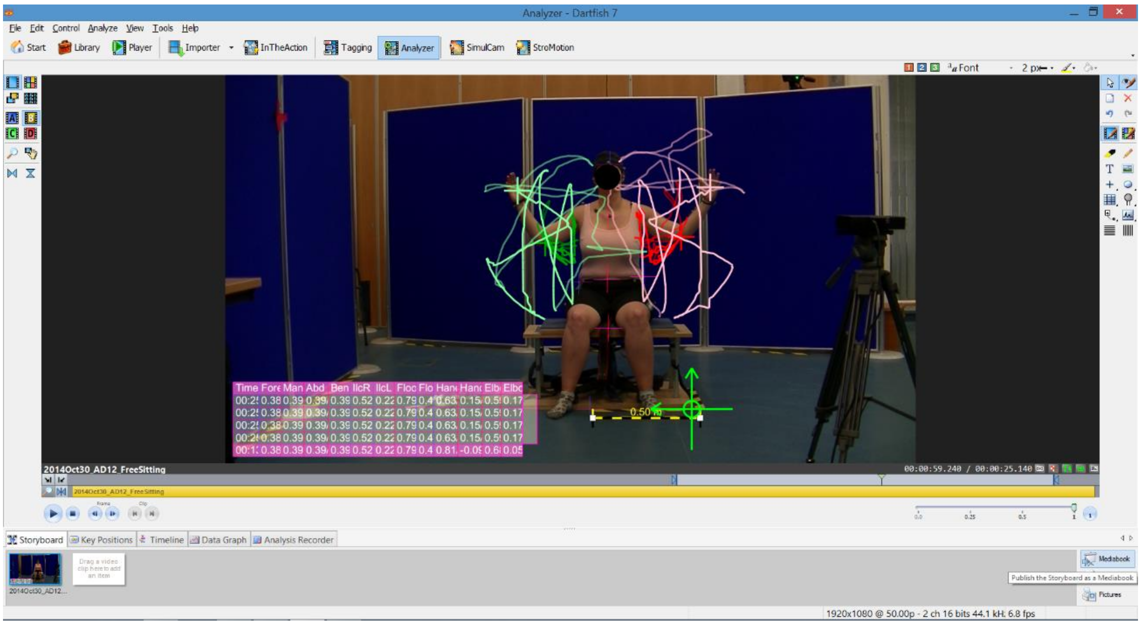

Figure VIII-12 Hands and Elbows Traces.

Showing a representative trial of the Hands and Elbows traces and the data table for the frontal markers.

Table VIII-1 Dartfish marker locations for the side view.

+ Head Left marker was used for the Adult-group; Head Right marker was used for the Child-group.

SEGMENT	Marker location description	Marker name
Head	Left/Right ear tragus Vertical from ear tragus	Ear Left/Right+ Head Left/Right+
Trunk	Spinous process of C7 Spinous process of T3 Spinous process of T7 Spinous process of T11 Spinous process of L3	C7 T3 T7 T11 L3
Pelvis	Spinous process of S1 Left/Right anterior superior iliac spine Left/Right greater trochanter	S1 ASIS Left/Right+ Hip Left/Right+
Upper limb	Lateral condyle of the humerus Left/Right	Elbow Left/Right+

Table VIII-2 Dartfish marker locations for the frontal view.

SEGMENT	Marker location description	Marker name
Head	Middle of the forehead	Forehead
Trunk	Clavicular notch	Manubrium
	Right iliac crest Left iliac crest	ILCR ILCL
Upper limbs (right and left)	Lateral condyle of the humerus	Elbow
	Head of the third metacarpal bone	Hand
Additional	Superior end of the bench	Bench

3. 3D Motion Capture System

3.1 General Information

3.1.1 What a 3D Motion Capture System Is

Three-dimensional (3D) motion capture systems are optoelectronic systems that can automatically identify the position of an object in space. To do this, the object's real dimension and position are defined using targets. The targets are small markers that are then recorded and reconstructed by the optoelectronic system to give a virtual representation of the object in space [91, 92]. Markers can be active or passive according to the signal generated. Active markers generate an infrared (IR) signal that is received by the optoelectronic cameras (Figure VIII-13) and later processed to identify the position of the targets in space. Passive markers are typically little spheres that reflect the IR light generated by the ring of infrared LEDs around the camera lens. The reflected light is received by the cameras and then processed to identify the position of the marker in space and consequently allow the reconstruction of the object [91, 92]. Passive optoelectronic systems are more frequently used.

3D motion capture systems are largely used in the recording, measurement and analysis of human movement, both in a clinical context and in sports and exercise. In clinical contexts 3D motion capture systems have generally been used for gait analysis, balance assessments and upper limb task execution; in sports they have been used, among others, for the analysis of non-traumatic knee injuries, and in vertical jump analysis as a measure of lower limb strength.

The purpose of the analysis will define which body segments are most relevant in each case and, in some cases, generate a customised marker set that will fulfil the objective of the analysis. There are, however, markers sets that are used worldwide; for example the Helen Hayes – Davis lower limb model for gait analysis, the six degrees of freedom (6DoF) developed both for gait analysis and for sport related lower limb movement analysis, or the plug-in-gait model which is a full body marker set developed for gait analysis [129].

Marker sets have most commonly been focused on the lower limbs. This is because gait analysis has been one of the most highly developed topics of human movement analysis [91]. However, studies have also looked at upper limb movement in relation to activities of daily living such as drinking from a glass, or in relation to mobility, for example manual wheelchair propulsion in patients with spinal cord injury [91].

3D motion capture systems are generally used indoors, as a key element for clean recordings is the elimination of any possible reflective sources that are not the body targets, and that the camera might therefore identify as markers. Elimination of unwanted reflections can be achieved with controlled illumination (indoors) but can represent a challenge with natural illumination. However, modern systems have developed cameras that can be used outdoors, for example in real sport scenarios [130].

3D motion capture systems offer an objective method for quantifying and analysing movement. 3D motion analysis is considered a gold standard for evaluating lower limb function during gait in different types of patients [91] and is presented as a standard reference for biomechanical research in other clinical scenarios and in sport and was used in this context for this work.

Figure VIII-13 Optoelectronic camera (Vicon Mx-F40).

3.2 Technical Characteristics

3.2.1 How 3D Motion Capture Systems Work

- Infrared cameras and markers

An infrared (IR) camera uses a non-visible light to get a circular reflection from the markers. IR lights are pulsed at 120Hz for a period of less than a millisecond; this light is reflected by the markers and then picked up by the IR cameras [131].

A minimum of two cameras is required for a 3D reconstruction of the position of one marker in space; however, three cameras should be defined as the minimum number of cameras required to reconstruct a marker to avoid complications related to marker obstruction during body movement. Specific arrangements of multiple IR cameras (six to twelve) are defined in relation to the test/trial requirements and the available space [91].

3D motion capture system analysis is based on the relation of the coordinates of an object in relation to the absolute coordinate system.

Cameras are typically distributed around the targeted volume where the action will take place and focused in relation to the distance to the targeted volume and the space light [91].

Camera calibration follows complex mathematical algorithms which result in the system triangulating the position of each camera in relation to an absolute coordinate system that represents the laboratory.

- Segment reconstruction

A minimum of three co-planar markers is required for the spatial reconstruction of an object. These markers define the proximal and distal ends of the object and the orientation in space; these basic/essential markers define the true size of the object and define the anatomical coordinates system of the object. If a given object has a redundant number of markers, a tracking coordinate system can be defined.

The relation of the tracking coordinate system to the anatomical reference, and of this to the absolute coordinate system, is what allows the tracking of the 3D object within the calibrated volume.

3.3 Vicon

3.3.1 What Vicon Is

Vicon (Vicon Nexus, Oxford, UK) is a commercially available motion capture platform used in clinical research, for tracking and measuring motion in real time [132].

3.3.2 How Vicon Was Used in This Project

- <u>Set up and calibration</u>

Ten Vicon MX-F40 cameras (Figure VIII-13) were distributed around the volume of interest as shown in Figure VIII-14 and Figure VIII-15 for the adults' and the children's data collection respectively.

After positioning, all cameras were focused following the guidance in the manufacturer's manual.

A calibration was performed before each data collection session and unwanted reflections were masked to improve the quality of the data collection. Calibration values were within the acceptable margins for the laboratory.

- <u>Data collection</u>

Data collection, marker reconstruction, labelling and gap filling was done using Vicon 1.8 for the Adult-group and Vicon 2.2 for the Child-group.

Data were collected at 100Hz using a customised Head-Trunk-Arms model (Table VIII-3, Figure VIII-16).

For the Adult-group, Vicon was start-stopped for each individual trial. For the Child-group, Vicon was left running and 60 seconds (maximum) trials were recorded; Vicon was start-stopped as many times as needed to obtain all the relevant clinical information.

A detailed description of the data collection procedures is included in each Study Chapter.

- Data processing

The procedures for data collection required the presence of more than one clinician within the calibrated volume with the participant. Despite the precise camera positioning and focusing, the presence of another person in the targeted volume inevitably resulted in marker obstruction. Marker obstruction occurred for a portion or the totality of the trial. For both groups, trials with totally obstructed markers on the relevant segments for specific trials were excluded from the analysis.

Marker obstruction generated gaps in the trajectory of the marker. Gaps were manually corrected using the 'gap filling tool' available options from Vicon: 'Spline Fill' uses an interpolation to fill the current gaps; 'Pattern Fill' uses the shape of another trajectory without gaps to fill the selected gap; or 'Rigid Body Fill' (Vicon 2) processing uses the information of three other markers that belong to the same rigid segment [132]. For the trials involving children, i.e. in a real clinical scenario, gap filling was a time-consuming task.

For the Child-group, long trials were cropped to match the video recording clips from the lateral and the frontal views. Manual synchronisation of the videos and Vicon was done in relation to clear specific movements of the child.

From each trial, the .c3d files with the labelled-markers coordinates (x, y, z) were saved and exported for further processing and analysis both in Visual 3D and in MATLAB.

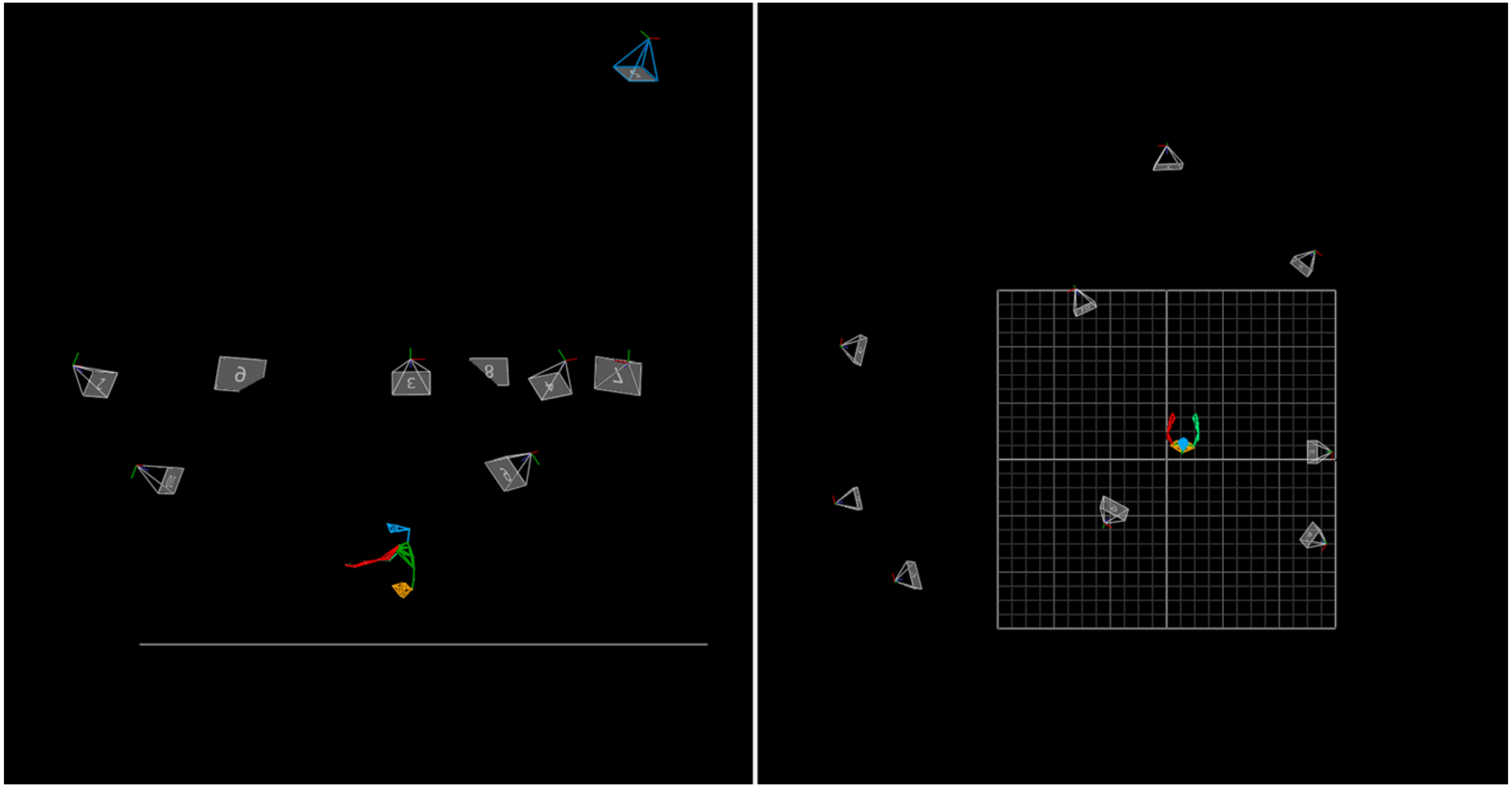

Figure VIII-14 Vicon camera setup for the Adult's group.

Showing the camera distribution around the participant from a lateral view from the left (left) and viewed from above (right).

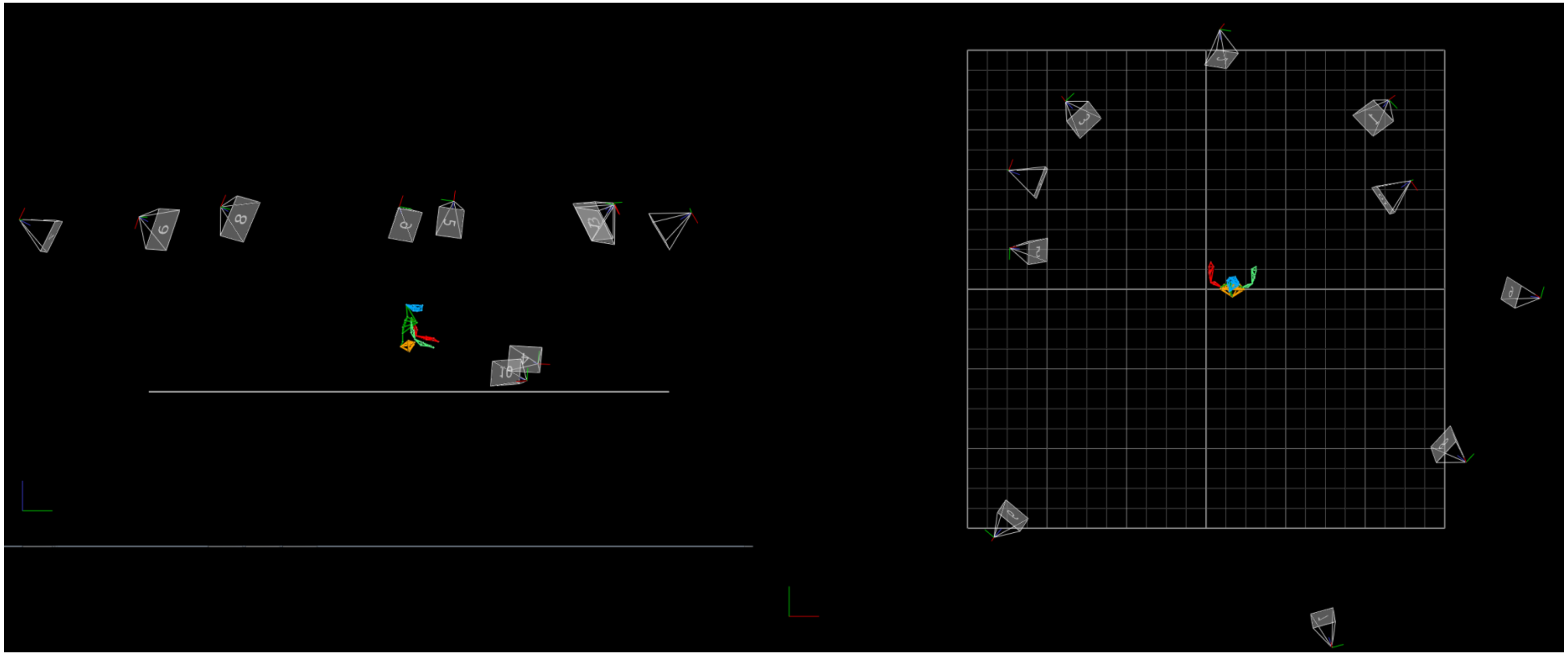

Figure VIII-15 Vicon camera setup for the Child's group.

Showing the camera distribution around the participant from a lateral view from the right (left) and from above (right).

Table VIII-3 Vicon marker locations.

SEGMENT		Marker location description	Marker name
Head	Head band	Middle of the forehead	Forehead
		External occipital protuberance	Head Back
		Right ear tragus	Ear Right
		Left ear tragus	Ear Left
		Prominent part of the right zygomatic bone	Face Right
		Prominent part of the left zygomatic bone	Face Left
		Vertical from ear tragus	Head Left (adult) / Head Right (child)
Trunk	Front	Clavicular notch	Manubrium
		Middle of the right clavicle	Clavicle
		Right acromion process of the scapula	Acromion Right
		Left acromion process of the scapula	Acromion Left
	Back	Spinous process of C7	C7
		Spinous process of T3	T3
		Spinous process of T7	T7
		Spinous process of T11	T11
		Spinous process of L3	L3
Pelvis		Spinous process of S1	S1
		Right iliac crest	ILCR
		Left iliac crest	ILCL
		Right anterior superior iliac spine	ASIS Right
		Left anterior superior iliac spine	
		Right greater trochanter	ASIS Left
		Left greater trochanter	Hip Right
			Hip Left
Upper limbs (right and left)	Upper arm	Cluster of three markers on a cork triangle, lateral side of the upper arm	Upperarm1 Upperarm2 Upperarm3
		Lateral condyle of the humerus	Elbow
	Forearm	Cluster of three markers on a cork triangle, lateral side of the forearm	Forearm1 Forearm2
		Styloid process of the radius	Forearm3
		Styloid process of the ulna	Radius
			Ulna
	Hand	Head of the third metacarpal bone	Hand

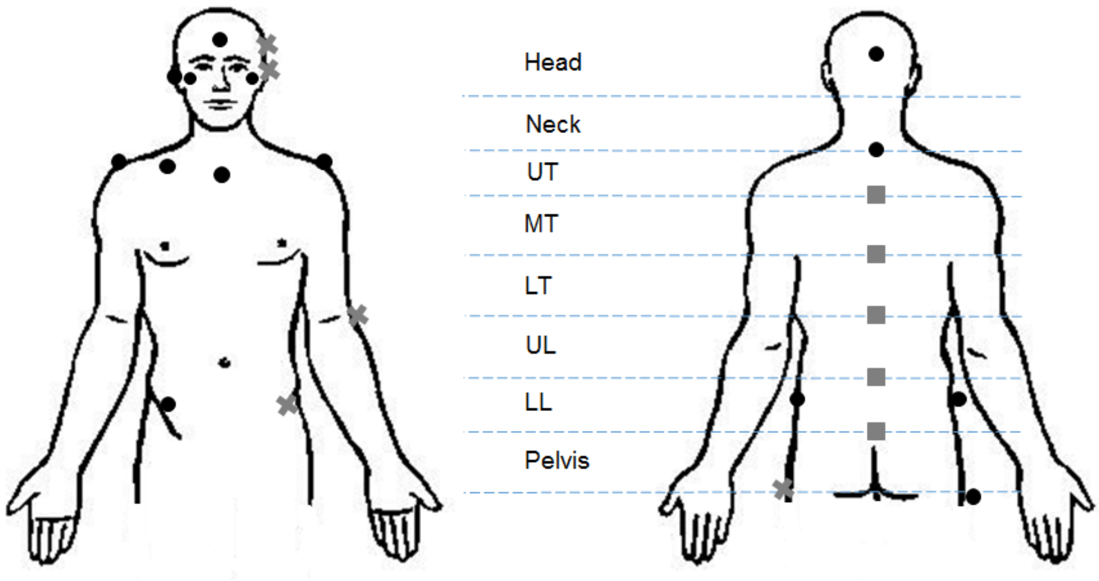

Figure VIII-16 Marker locations and limits of trunk segments.

Dots show Vicon marker locations: forehead, occipital protuberance (Head Back), zygomatic bone (right and left, Face), right ear tragus (Ear Right), clavicular notch (Manubrium), middle of the right clavicle (Clavicle), acromion process of the scapula (right and left, Acromion), spinous process seventh cervical vertebra (C7), iliac crest (left and right), and right anterior superior iliac spine (ASIS Right) and greater trochanter (Hip Right).
Crosses show reflective markers used additionally for Video tracking: left ear tragus (Ear Left), left temporal fossa (in a vertical line from the ear tragus when the head was in neutral position, Head Left), left anterior superior iliac spine (ASIS Left) and greater trochanter (Hip Left).
Squares show reflective markers that had an equivalent coloured block: spinous process of the third, seventh and eleventh thoracic vertebrae (T3, T7 and T11), third lumbar vertebra (L3) and first sacral vertebra (S1).

3.4 Visual3D

3.4.1 What Visual 3D Is

Visual3D (V3D, v.5.01, C-motion, Germantown, MD, USA) is a biomechanics analysis software for 3D motion capture data [133]. It is used worldwide in both clinical and research contexts.

3.4.2 How V3D Was Used

The .c3d files exported from Vicon were opened in Visual3D.

A model template was created as shown in Figure VIII-17 to allow the calculation of movement of the separate segments. The model required the creation of virtual markers (landmarks) to create the trunk segments or to generate more accurate segments (head or upper arms). The parameters used to create the virtual markers are described in Table VIII-4. A detailed definition of the segments is included in Table VIII-5.

A pipeline was created to facilitate the V3D analysis, and then run separately for each participant. The pipeline comprised:

i) Creation of the participant's model based on the template model and the participant's weight and height.

ii) Assigning of the participant's model to the dynamic trials.

iii) Low-pass filter at 6Hz to filter marker trajectories.

iv) Calculations of the segmental angles for the Head, Neck, Trunk segments and Pelvis. This was done using the 'Compute Based Model' command in relation to the absolute coordinate system ('LAB').

v) Calculation of the centre of mass of the Hand (left and right) and calculation of the distal centre of mass of the Upper Arm segment (left and right).

vi) Saving the workspace as a C-Motion Output (.CMO).

vii) Exporting the marker trajectories, segmental angles, and centres of mass to a Matfile (.mat).

3.4.3 What Resulted from V3D

The data saved in the .mat files was used for further analysis in MATLAB.

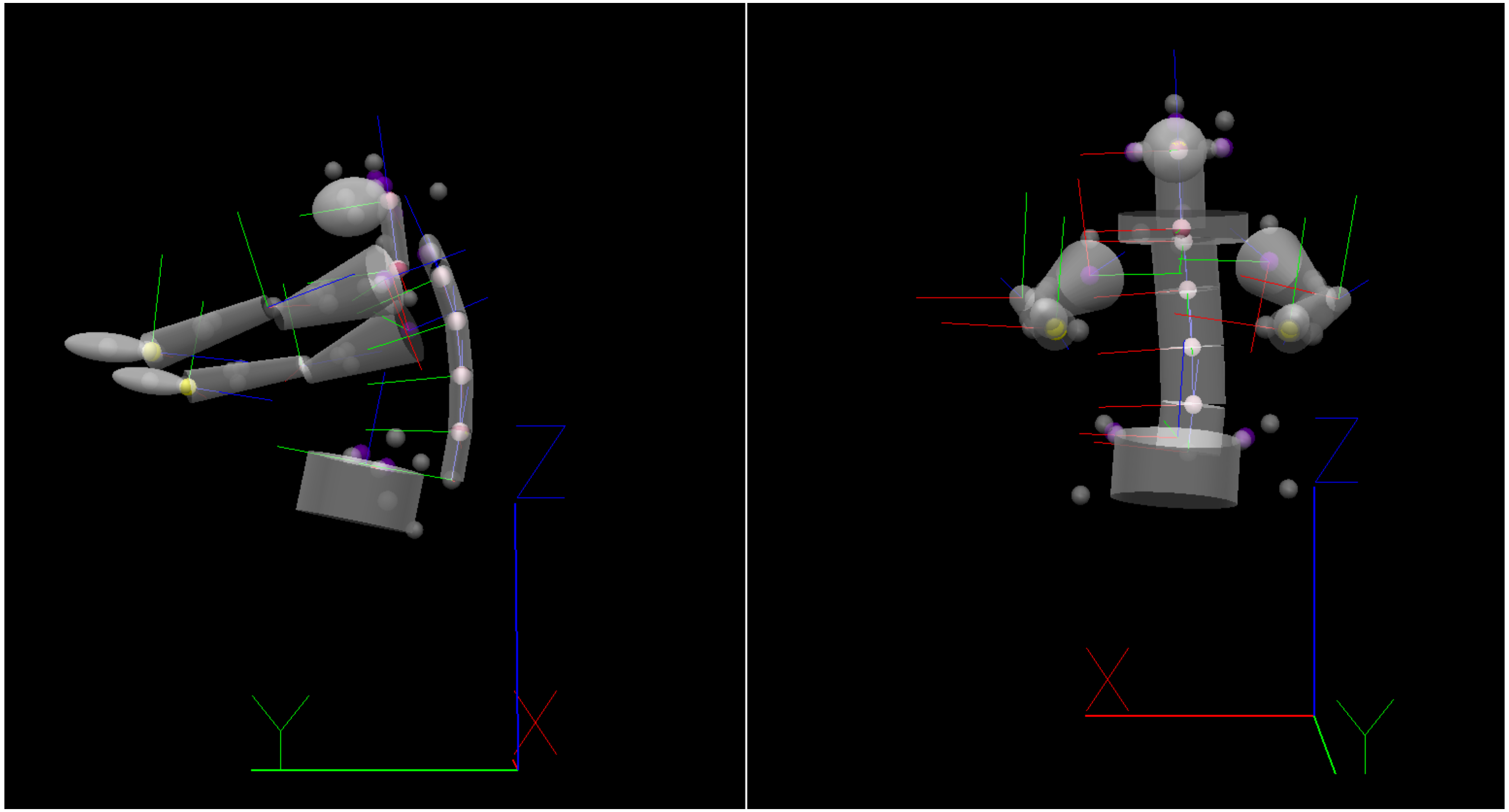

Figure VIII-17 Example of the model created from Visual3D.

Table VIII-4 Virtual marker definitions.

Virtual Marker	Starting Point	End Point / Reference	Offset
Mastoid Right	Ear Right	Face Right	Axial -0.02m
Mastoid Left	Ear Left	Face Left	Axial -0.02m
Head Centre of Mass (COM)	Mastoid Right	Mastoid Left	Axial 0.5%
Trunk top	Manubrium	C7	Axial 0.5%
C7 virtual (C7-v)	C7	Manubrium	Axial 0.01m
T3 virtual (T3-v)	T3	LAB	X = 0.00001 Y = 0.0 Z = 0.0
T7 virtual (T7-v)	T7	LAB	X = 0.00001 Y = 0.0 Z = 0.0
T11 virtual (T11-v)	T11	LAB	X = 0.00001 Y = 0.0 Z = 0.0
L3 virtual (L3-v)	L3	LAB	X = 0.00001 Y = 0.0 Z = 0.0
Shoulder joint centre Right	Acromion Right	LAB	X = 0.0 Y = 0.0 Z = -(Marker_Radius + 0.17*Distance(Acromion Right, Acromion Left)
Shoulder joint centre Left	Acromion Left	LAB	X = 0.0 Y = 0.0 Z = -(Marker_Radius + 0.17*Distance(Acromion Left, Acromion Right)

Table VIII-5 Definition of the segments in Visual3D.

+ Virtual marker. ASIS = Anterior Superior Iliac Spines.

Segment	Proximal end	Distal end	Tracking markers	Orientation / Depth
Head	Mastoid Right+ Mastoid Left+	Face Right Face Left	Head Back Forehead Ear (left, right) Face (left, right)	
Neck	Trunk top+	Head CoM+	Head CoM+ C7 C7-v+	
Upper-Thorax	T3	C7	C7 T3 T3-v+ Clavicle Manubrium	Manubrium (anterior) 0.25m
Mid-Thorax	T3	T7	T3 T3-v+ T7 T7-v+	T3-v+ (lateral) 0.25m
Lower-Thorax	T7	T11	T7 T7-v+ T11 T11-v+	T7-v+ (lateral) 0.25m
Upper-Lumbar	T11	L3	T11 T11-v+ L3 L3-v+	T11-v+ (lateral) 0.25m
Lower-Lumbar	L3	S1	L3 L3-v+ S1	L3-v+ (lateral) 0.25m
Pelvis	Helen Hayes pelvis: ASIS (left, right) S1 (posterior)		Iliac crest (left, right) ASIS (left, right)	
Upper arm (left/ right)	Acromion Shoulder joint centre+	Elbow	Cluster 3 markers	Distal radius 0.025m
Forearm (left/ right)	Elbow	Wrist (medial, lateral)	Cluster 3 markers	Proximal radius 0.025m
Hand (left/ right)	Wrist (medial, lateral)	Hand	Wrist (medial, lateral) hand	Distal radius 0.03m

4. MATLAB

4.1 General Information

Matrix Laboratory (MATLAB, Mathworks, Cambridge, MA) is a general mathematical tool. Using a scripting language, it is possible to write algorithms to perform data operations and calculations, allowing multiple approaches for data analysis.

MATLAB (version R2015a) has toolboxes that make it compatible with hardware and software applications. They implement complex and well established commercial applications to enable specific signal processing.

4.2 How MATLAB Was Used

Different codes were written[35] to do all the customised post-processing and analysis of this project. The codes can be grouped in relation each study (Figure VIII-18, Figure VIII-21, Figure VIII-22).

[35] Codes were written by others (supervisors) who were not the author of this thesis. The author of this thesis (PhD Student) was in involved iteratively in the design and specification of the analysis scripts. The author of this thesis made adjustments to make the scripts run from her computer, as well as modifications to the different parameters and to perform different 'levels' of processing. She then closely verified the time series of every calculation for every trial and every result to ensure the analysis was performing correctly.

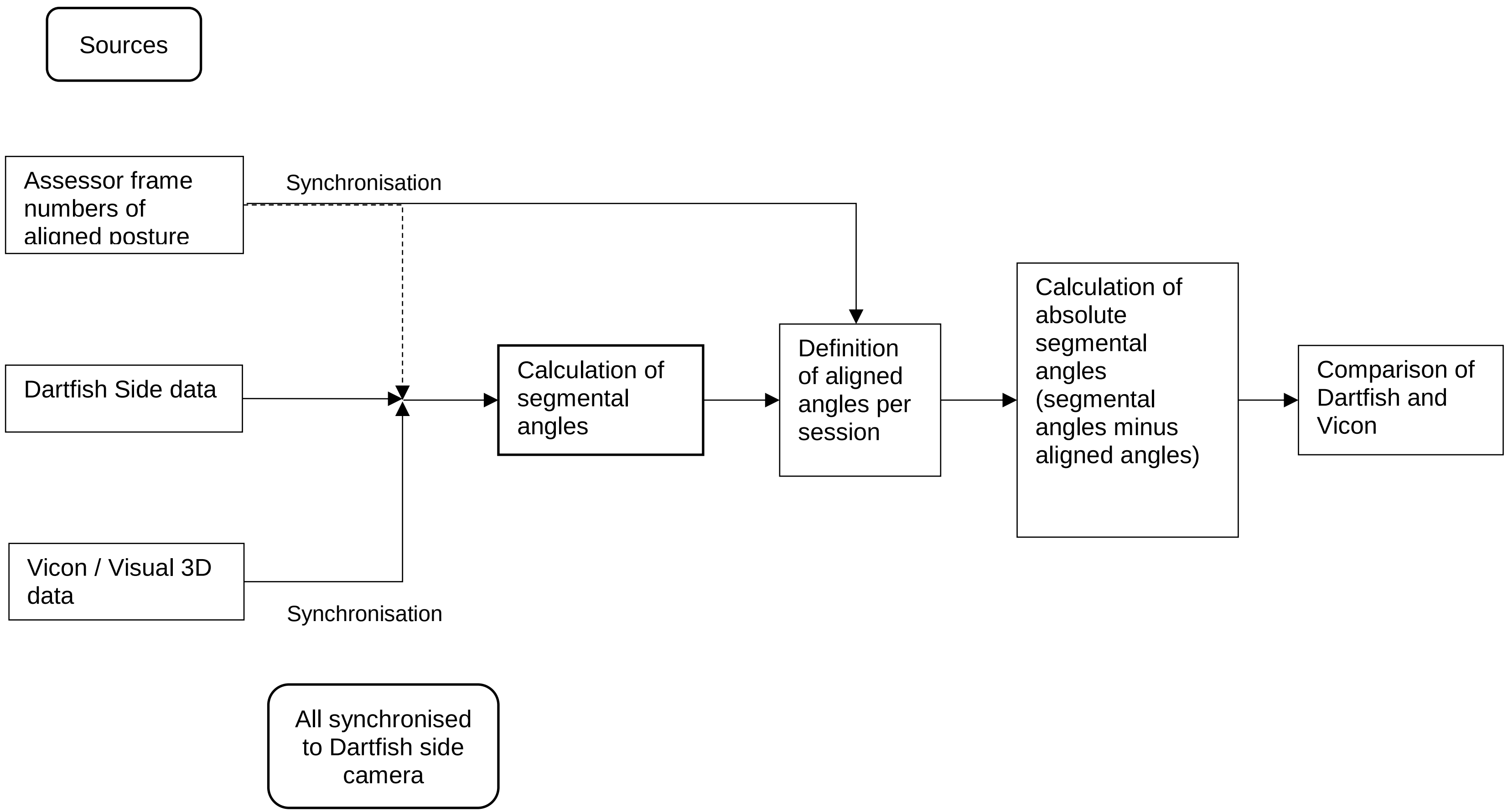

Figure VIII-18 Diagram of the ‘Alignment Study’ MATLAB script for processing and analysis.

4.2.1 Alignment Study

The ‘Alignment Study’ (Chapter IX) code used three sources of data for processing and analysis (Figure VIII-18): frame numbers where posture was aligned that was provided by the assessors; x and y coordinates of the head and trunk markers, obtained from Dartfish processing of the side view videos; and 3D motion data, marker coordinates (x, y, z) from Vicon and segmental angles calculated in Visual3D.

All sources were synchronised to the Dartfish side view data; this was done using an initial manual synchronisation based on the information provided by the displacement of the markers in time (Figure VIII-19). The manual synchronisation was followed by an automated fine-tuning using cross correlation. Cross correlation was used to find the time offset (adjustment) that gave maximum agreement between Dartfish side view signals and Vicon signals.

Segmental angles were calculated from this synchronised data. For the 2D video-based data, a segment was defined as the vector joining two consecutive landmarks. For each segment, the segmental angles were estimated. A segmental angle represents the position of a segment in relation to a vertical line and was calculated following the dot product formula:

$$\mathrm{B} \cdot \mathrm{C} = ||\mathrm{B}||||\mathrm{C}|| \cos \mathrm{A_s}$$

where B represents the segmental vector between two consecutive landmarks, C represents the upright vertical vector, ||B|| represents the magnitude of the vector, A the angle of a segment, and *s* represent each segment. From which

$$\cos \mathrm{A_s} = \frac{B \cdot C}{||\mathrm{B}||||\mathrm{C}||}$$

and

$$\mathrm{A_s} = \mathrm{acos} \frac{B \cdot C}{||\mathrm{B}||||\mathrm{C}||}$$

Segmental angles (A_s) calculated with this method were used in the clinical video tracking analysis.

For the 3D motion data, segmental angles were extracted from the .mat file created in Visual3D. For the 3D segmental angles, only the sagittal component was included in the analysis i.e. the comparison between methods used only the equivalent information to video.

A model of alignment of each participant was then constructed based on an agreed definition of postural alignment in sitting, and was created using the segmental angles (A_s) following these steps:

i) Visual identification of frames where posture was aligned made from each separate video. Five clinicians with expertise in posture analysis independently rated the videos and identified the frames where the participant's posture was aligned following the defined guidelines

ii) The video frames where posture was identified as aligned were then used to obtain the aligned angles for each segment. This process also enabled aligned segmental angles to be obtained relative to the synchronised Vicon trials.

iii) The aligned angles of each participant, were used to define their aligned posture. This was expressed as the set of mean ± standard deviation (SD) values for each aligned segment. (Figure VIII-20).

Using the aligned angles (A_a) as reference absolute segmental angles (A_{sa}) were calculated as:

$$A_{sa} = \mathrm{A}_s - A_a$$

The absolute segmental angles (A_{sa}) were then used for comparison between Dartfish (DA_{sa}) and Vicon (VA_{sa}). The disagreement between methods was calculated as the root mean square error (RMSE) between signals for each segment:

$$\mathrm{RMSE_s} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{DA}_{sai} - \mathrm{VA}_{sai})^2}{n}}$$

Where *n* represents the number of instances of a trial and *i* stands for all the instances of a trial.

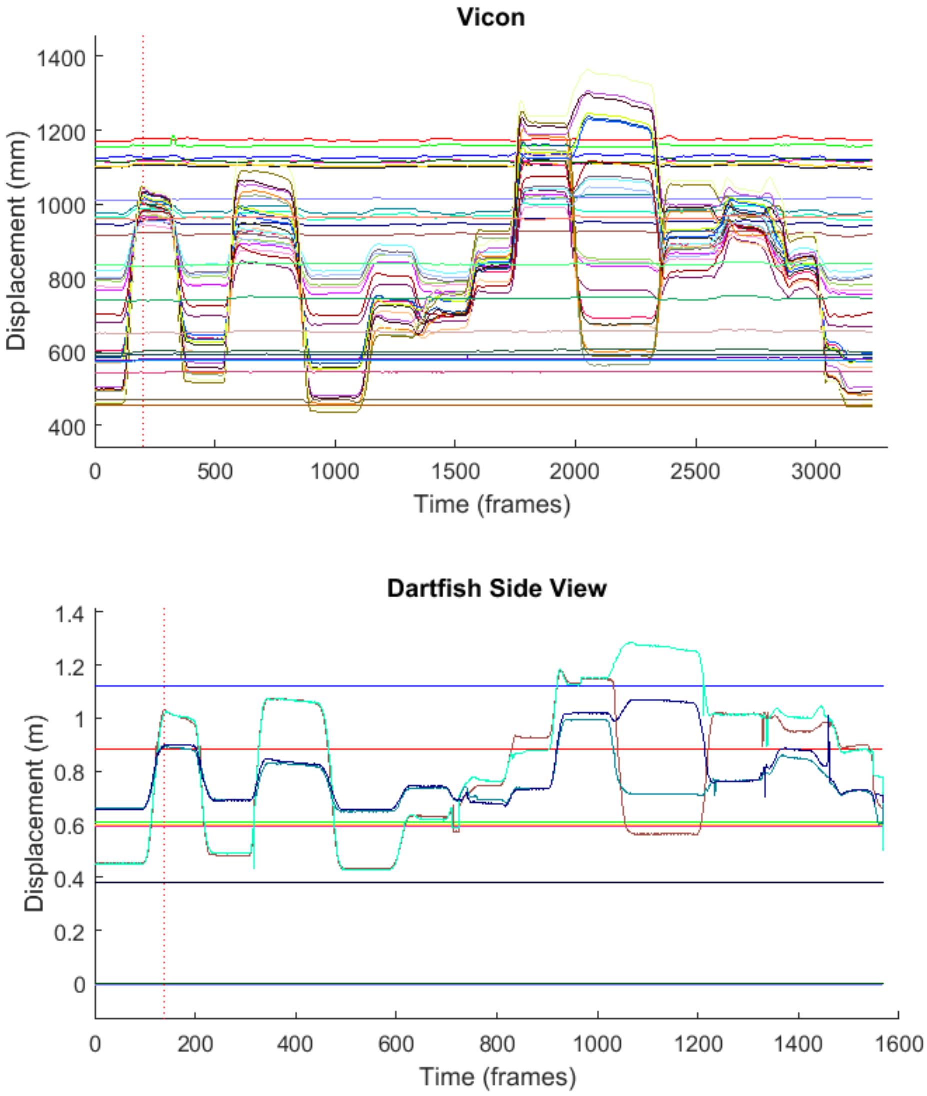

Figure VIII-19 Example of Manual synchronisation.

Showing the traces of the markers displacement for Vicon (top) and Dartfish (bottom). The red vertical dotted line shows the moment manually identified to be used as reference for synchronisation.

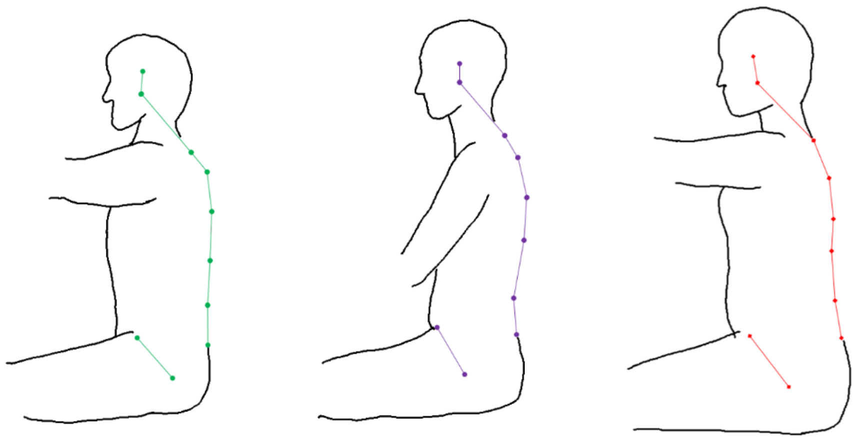

Figure VIII-20 Mean aligned segmental angles for three participants. Models created from the 2D-video data.

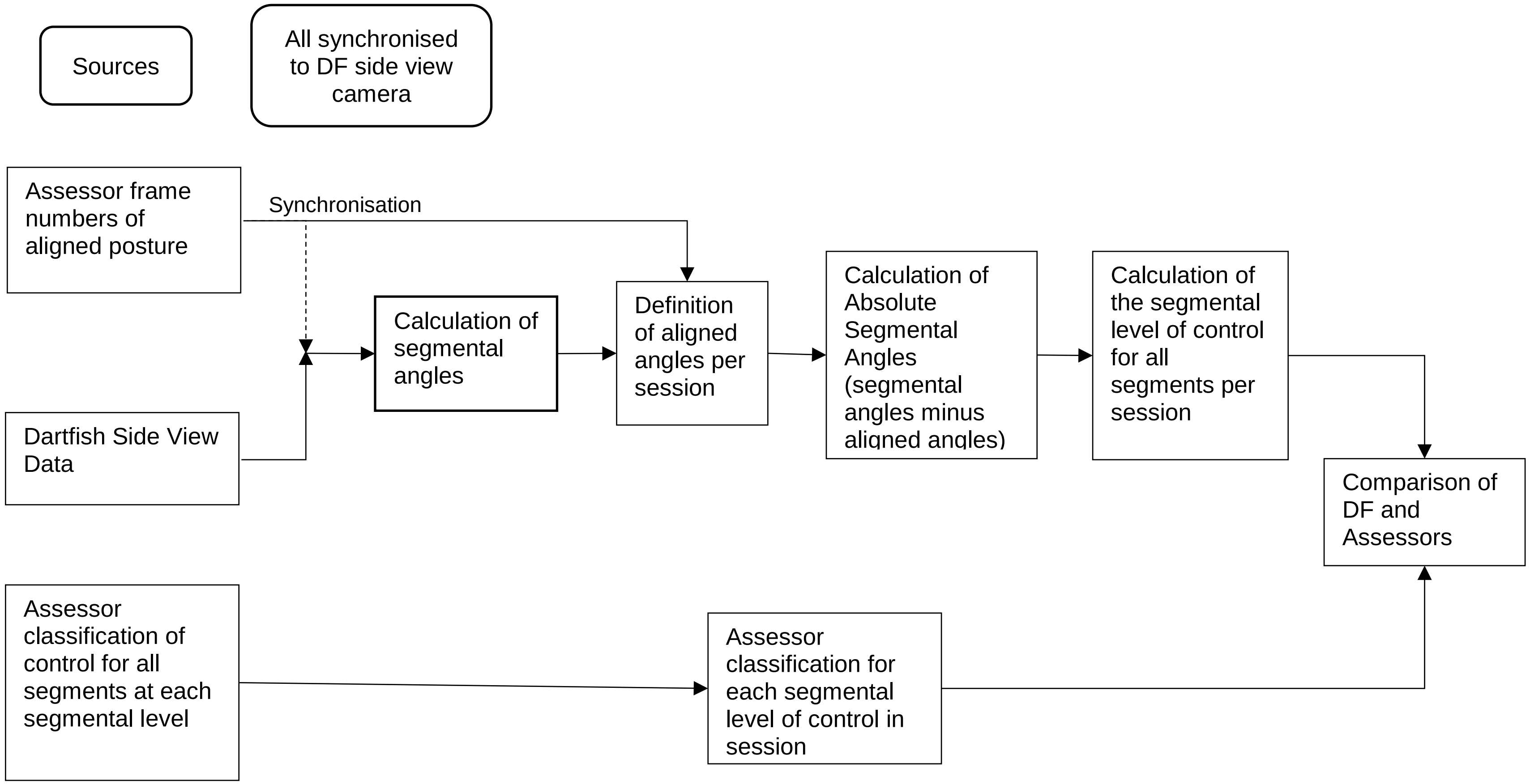

Figure VIII-21 Diagram of the 'Levels of Control Study' MATLAB script for processing and analysis.

4.2.2 Levels of Control Study

For processing and analysis of the ‘Levels of Control Study’ (Chapter XI), three sources of information were loaded into MATLAB (Figure VIII-21): frame numbers where posture was aligned provided by the assessors; x and y coordinates of the head and trunk markers, obtained from Dartfish processing of the side view videos; and the clinical classification for each segmental level of control tested.

Synchronisation, calculation of segmental angles, definition of aligned angles per session and calculation of absolute segmental angle, were done following the process described above for the ‘Alignment Study’ (Section 4.2.1).

The absolute segmental angles were used to calculated different variables (mean angle, standard deviation, absolute mean deviation plus SD, and maximum absolute angle deviation) that allowed the generation of an objective measured segmental level of control. Details of how the variables and the objective measure segmental level were calculated can be found in context in Chapter XI.

The clinical classification for each segmental level of control was expressed as the clinicians’ classification of the level of control of a child per session. This was then compared with the objective measured level of control for validation of the objective measure. Agreement between the objective and the clinical judgement was calculated as the mean error (ME) and the root mean square error (RMSE).

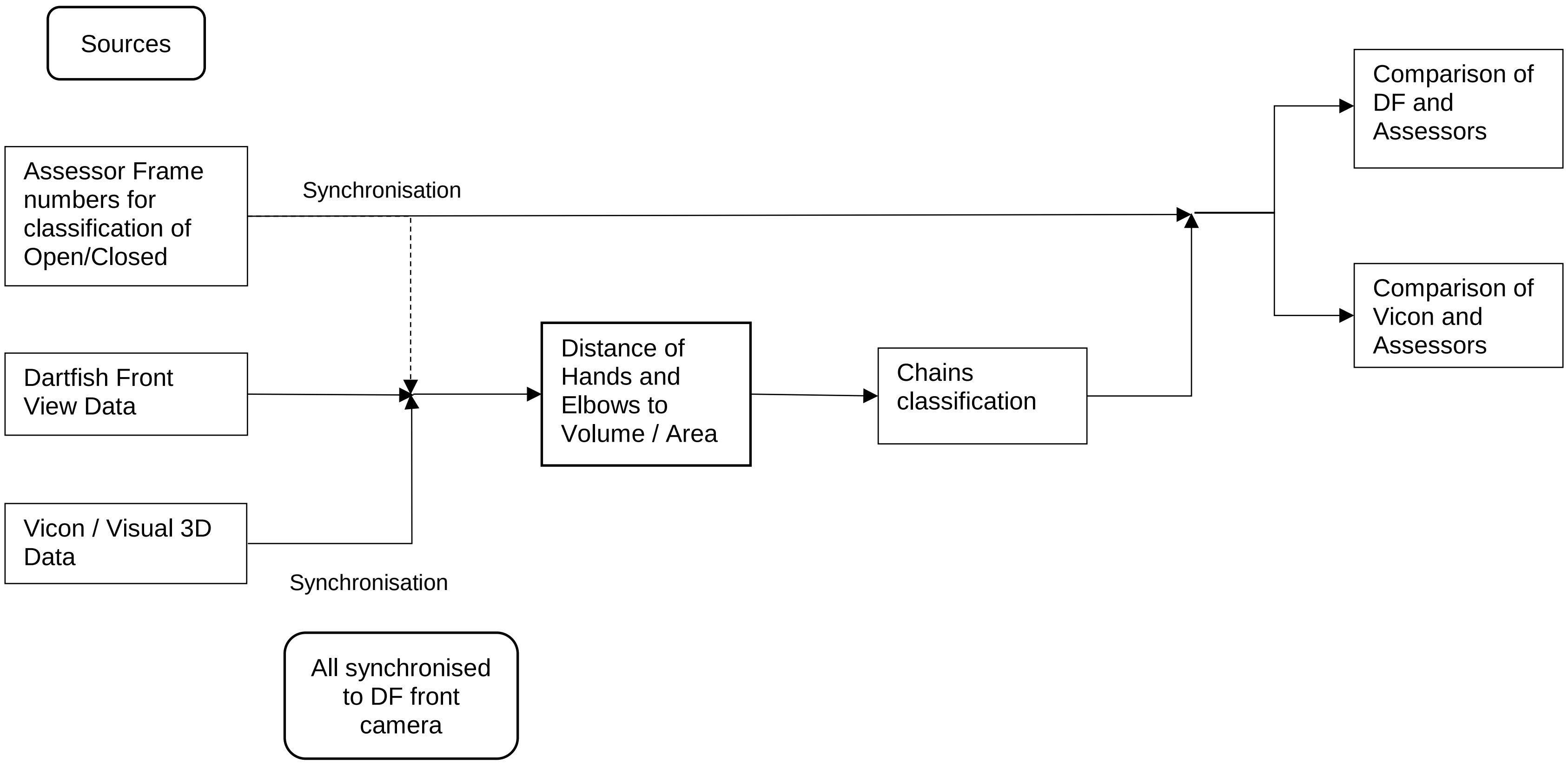

Figure VIII-22 Diagram of the 'Upper Limb Study' MATLAB script for processing and analysis.

4.2.3 Upper Limb Study

For the 'Upper Limb Study' (Chapter X) three sources of data were loaded into MATLAB (Figure VIII-22): frame numbers provided by the assessors for the classification of Open or Closed Controlled Kinetic Chains (Open-CKC or Closed-CKC); x and y coordinates of the hands and elbows, obtained from Dartfish processing of the frontal view videos[36]; and 3D motion data, marker coordinates (x, y, z) from Vicon and Visual3D.

All sources were synchronised to the Dartfish front view data; for the Adult-group this was done using an initial manual synchronisation based on the information provided by the displacement of the markers in time followed by an automated fine-tuning using cross correlation. For the Child-group synchronisation was done identifying a common frame for the frontal video and Vicon.

From Dartfish and/or Vicon data a 'supported-body' was defined. The 'supported-body' represents the trunk and the external objects, including the primary support surface, that can be used by the upper limbs to provide external mechanical support to the trunk. For example, if the participant rests one hand on the bench, there will be an additional support, also if the hand was on the leg or head. For the video, the supported-body comprised the area covering the body and the bench. The body was considered the rectangular area between the iliac crest markers (width) and between the bench mark and the forehead (height). The bench was the area below the horizontal line passing through the bench mark (Figure VIII-23). For the 3D data, the supported-body was defined by the body of the participant and the bench. The body was represented by a 3D cylindrical volume covering the head-trunk and pelvis, that used the distance between the iliac crest markers as the diameter of the cylinder, and the distance between the midpoint between the greater trochanter markers to the forehead marker +5cm as height of the cylinder. The bench was defined as the volume below the greater trochanter markers (Figure VIII-23).

The position of the hands and elbows was defined by the coordinates obtained from Dartfish for the frontal videos (x, y) and by the Visual3D for the 3D data (x,

[36] Dartfish coordinates from the frontal view videos were only available for the Adult-group.

y, z); the distance of hands and elbows to the supported-body was then calculated.

The shortest distance from the hands and elbows to the supported-body was used to classify the position of the upper limbs as supporting or not, i.e. to define a Closed-CKC or an Open-CKC[37]. An Open-CKC was present when all distances (both hands and elbows) were larger than a defined threshold (> *t* mm).

$$OpenCKC = all\left(\begin{bmatrix} d1 \\ d2 \\ d3 \\ d4 \end{bmatrix} > t\right)$$

The threshold is an adjustable parameter that represents a margin required to determine when the upper limb is definitely clear of the supported-body.

The agreement between signals (Vicon v Clinical, or DF v Clinical) was calculated as the percentage of time during which the classifications were the same for each trial (Figure VIII-24). Comparisons were made between the clinical identification of Open-CKC and the video-based classification for the Adult-group, between the clinical judgement and the objective classification from the 3D motion system for both groups, and between the video based and the Vicon based classification of Open-CKC for both the child and the Adult-group. The calculated agreement between signals was exported to an Excel book (.xlsx) for further analysis.

[37] See Chapter V for a detailed explanation of the implication of hand support.

$$OpenCKC = all\left(\begin{bmatrix} d1 \\ d2 \\ d3 \\ d4 \end{bmatrix} > t\right)$$

where *t* is an adjustable threshold

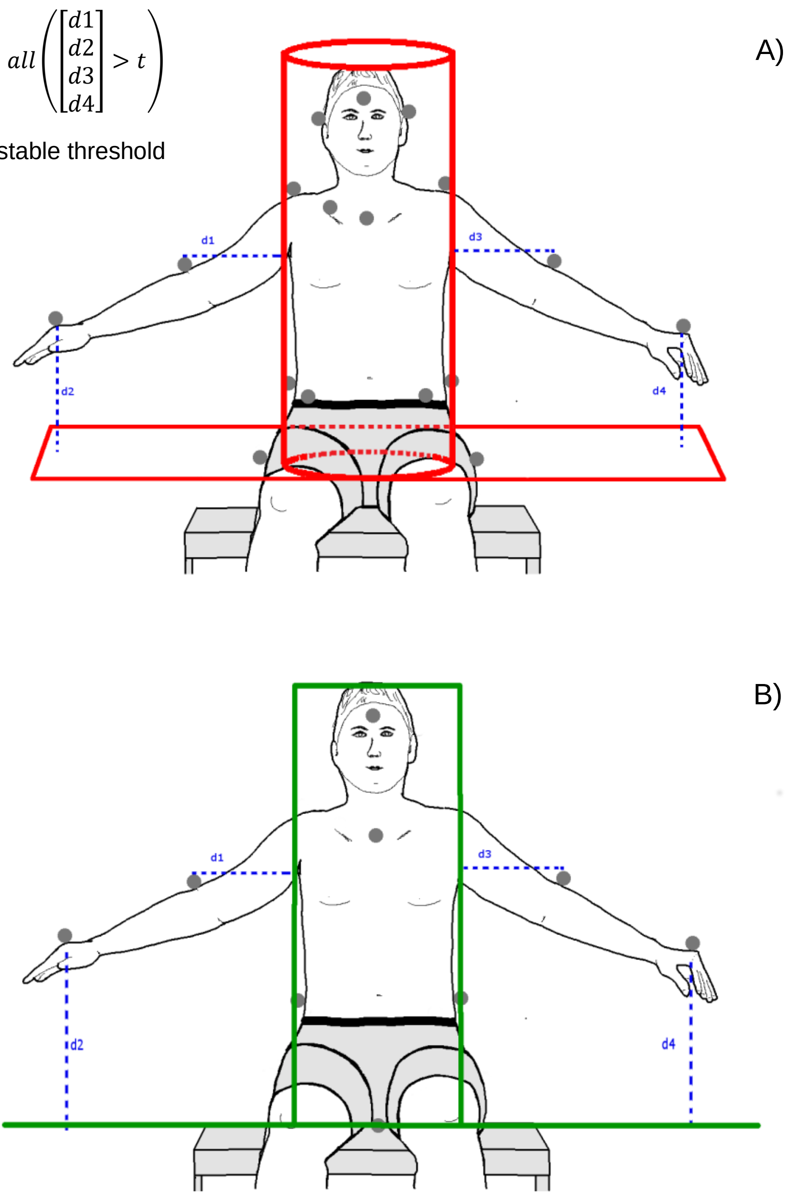

Figure VIII-23 Marker locations and supported-body.

A) Dots show Vicon marker locations: forehead, middle of the right clavicle, left and right acromion process of the scapula, lateral condyle of the humerus (elbow), head of the third metacarpal bone, Iliac crest, anterior superior iliac spine and greater trochanter. The red cylinder and plane represent the volume that defined a Closed-CKC.

B) Dots show Dartfish marker locations: forehead, lateral condyle of the humerus (elbow), head of the third metacarpal bone, Iliac crest, and superior end of the bench. The green rectangle and line represent the area that defined a Closed-CKC.

Dashed blue lines (A, B) show the shortest distances ($d_{1\text{-}4}$) from each of the hands and elbows to the supported-body surface for this given posture.

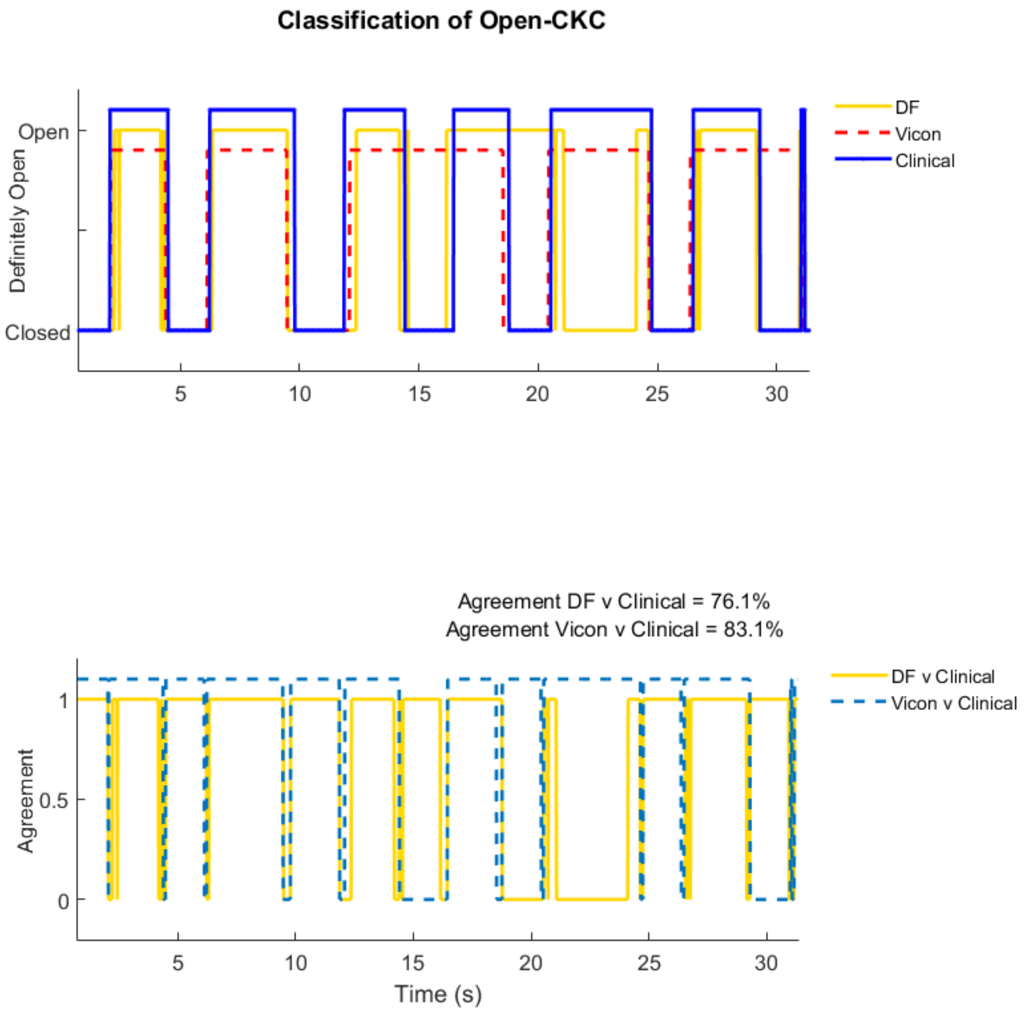

Figure VIII-24 Representative example of Open-CKC classification and agreement calculation.

Showing the Open-CKC classification (top) for Dartfish (DF, bold yellow line), Vicon (dashed red line) and clinical (bold blue line), and the calculated agreement along time for Dartfish (DF) v Clinical (bold yellow line) and for Vicon v Clinical (dashed blue line).

5. Other Approaches

The literature describes other systems that offer the possibility of developing a quantitative assessment method for the identification of both an Open Controlled Kinetic Chain and a Closed Controlled Kinetic Chain. Among the systems available, Kinect (Microsoft Kinect) represents a potential option for use in a clinical setting as it does not require markers to be attached and it is not expensive equipment.

5.1 Kinect

The Microsoft Kinect™ is a non-invasive human pose estimation (NIHPE) system based on a RGB-D camera. A Kinect camera allows Red-Green-Blue (RGB) colour channels to be captured, and additionally captures a Depth (-D) channel. The world is then represented as a rectangular matrix of picture elements (pixels); for each pixel a RGB-D camera will give four values: red, green, blue and depth. This output is closer to that of both human eyes [134] for identification of an object in space.

Research has been focused on developing NIHPE approaches from the RGB-D images obtained from a Kinect camera. One important part of the research was based on the possibility of training a machine (machine learning) to identify (using the RGB-D values of a given pixel) the part of the body surface to which that pixel belonged [135]. A second approach used a skeletal tracking algorithm that took the previous pixel classifications and attempted to 'fit' a simple 3D skeleton (composed of 20 joints) to them [136]. Both of these approaches were developed on adults and older children by the Microsoft research teams.

Outside the Microsoft research groups, the information generated from the 3D skeleton can be recorded thanks to a Microsoft Software Development Kit (SDK); however, the underlying information and algorithms used to calculate the position of the joints or to subtract the body from the background are not available to independent researchers. The SDK can provide real-time anatomical landmark position data in three-dimensional space (for example, the position of the hands), allowing the identification of objects in space [137]. This feature was the reason that Kinect was tested to determine its suitability in the present project[38].

Despite its potential for the identification of a 3D skeleton, Kinect was found to have limitations in the present work. The first limitation was poor subtraction[39] of the participant, which resulted in poor identification of his/her position and interaction with surrounding elements. The original development of the SDK was with the Kinect directly in front of the person; in the present work, it was necessary to place the Kinect in an oblique position in relation to the participant due to the specific requirements of the assessment. Although there is no definite information, it is possible that this oblique camera position resulted in the poor subtraction of the participant from the background and the consequent problems with the skeletal tracking estimation.

A second limitation may have been related to the fact that participants of the present project had to be sitting and in many cases required external trunk support (provided by a person kneeling behind them). Users of Kinect generally stand in front of the camera, which results in a clear subtraction of the person from the background and good skeletal tracking. The sitting posture also introduced a further surface (of the bench) and this, combined with sitting rather than standing may have contributed to poorer body subtraction. Furthermore, inability to access the algorithms to subtract the body from the background meant that changes in the information to adjust it to the protocol followed in this project were not possible.

Finally, in those cases where it was possible to separate the participant from the background the skeleton tracking estimation showed poor performance. The skeleton tracking algorithm was created on adults and older children. The children taking part in this project were young children (2-11 years old). It is probable that the children did not reach the minimum size that Kinect requires for skeletal

[38] The pilot work that generated the following conclusions was led by Dr John Darby. Data was collected simultaneously to the PhD data collection. Processing and analysis was performed independently by Dr Darby. The PhD student had access only to discussion of the conclusions. However, these conclusions are presented here as Kinect may, at first consideration, appear to be an ideal tool for this type of work.

[39] Subtraction', also known as 'background segmentation' is the process of separating the pixels of interest from the other pixels in the scene – in this case human pixels from their surroundings.

tracking. Adjustments could not be made as there is limited access to this information.

The data tested in the pilot work by Dr Darby was based on the outputs obtained from the SDK. The SDK was developed by a machine training process with the Kinect placed directly in front of the adult user [135, 136]. The RGB-D information that can be obtained from a Kinect camera can, however, be used for the development of new algorithms that would take account of the limitations and requirements of the specific clinical assessment, as well as the anthropometric characteristics of the children. This development would require a new machine learning process independent of the SDK outcome. This would be a major undertaking but has great future potential. However, the existing limitations of Kinect meant that its use was not pursued for the present project.

6. Conclusion

This chapter presents the methods used for the data collection, data processing and analysis in this project.

Video recordings are a method that is commonly found in a clinical practice. 2D-videos can provide qualitative information of an assessment but, most importantly, the use of appropriate analytical tools (e.g. Dartfish) means that 2D-video recordings have the potential to provide quantitative information.

3D motion capture systems (e.g. Vicon) are considered the ‘gold standard’ for movement analysis. Although there are several limitations with these systems which makes them impractical for use in a physiotherapy practice for the assessment of trunk control, 3D systems serve as an objective standard reference for the development of other analytical methods based, for example, on video recordings.

In the present project, from the data obtained from 2D-videos and 3D motion capture, further processing and analysis was done using MATLAB. MATLAB allowed the development of customised scripts enabling comparative analysis between the different sources of information (clinicians, Dartfish, Vicon-V3D).

While other methods might have been appropriate in the present project, the combination of 2D videos, 3D motion capture and MATLAB has enabled the development of a quantitative identification of the components of motor control, as presented in the following Chapters.

Studies

IX. Quantification of Seated Postural Alignment of the Head and Trunk

1. Introduction

Posture is traditionally assessed subjectively to evaluate the musculoskeletal changes that can result from poor postural habits or as a consequence of a neuromuscular condition. Although subjective assessments of posture are based on a 'common knowledge' of the 'ideal posture' in standing or sitting, the use of general terms such as 'slightly anterior' or 'slightly posterior', used in standing assessments, allow a wide range of interpretation. The 'ideal posture' in sitting tends to be further limited. Objective quantification is thus desirable to address the limitations of subjective assessments, to quantify changes in patients that result from therapeutic intervention, or monitor the progression of a neuromuscular condition. This was confirmed in the Literature Review 'Assessment Methods of Postural Alignment' of this thesis which found only fair to poor reliability between observers[40] [64, 65].

Various methods of quantifying aligned sitting posture are suitable in a research environment. Translation of these methods to a clinical environment is, however, difficult. Three-dimensional (3D) motion capture systems, for example, require the markers to be constantly visible to allow the segment reconstruction. This may not represent a challenge in the assessment of more able patients, or those that can actively co-operate; however, patients with neuromotor disabilities very often require assistance to maintain an upright posture in both sitting and standing. This inevitably means that some markers are obscured thus affecting accuracy of measurement.

Furthermore, in most 3D models the trunk is usually considered as a single unit, from the shoulders to the iliac crests. This simplified representation of the trunk

[40] Refer to Chapter IV (Section 2) for a detailed description of how the use of general terms affects the reliability of the traditional assessment of posture.

ignores the fact that the large range of movement of the trunk is the result of the combined movements of adjacent vertebrae. The range of movement varies throughout the trunk and is not uniformly distributed. Additionally, 3D motion capture systems are expensive with demanding data collection protocols and processing that make them impractical in a clinical context. However, despite the limitations described here and in previous chapters, 3D motion capture systems remain a 'gold standard' for validation of other measurement systems, for example video recordings.

The 'Assessment Methods of Postural Alignment' Literature Review thus identified the use of video recordings as the most practical clinical method since they require minimal technical and patient preparation and can be used with all ages and severity of disability. But to combine both Literature Review findings, the quantification of these video assessments is essential both for validation against the 'gold standard' and for the generation of an objective measurements of postural alignment.

The overall Objective of this project was to develop a clinical tool for objective quantification of postural control in children with cerebral palsy (CP). This required a separate development of instruments for the assessment of the different components of control[41]. The aim of the study reported here[42] was to develop a video-based method to quantify seated postural alignment of the head and trunk and to be able to identify any deviation from the aligned posture. This study thus incorporates the definition of the concept of alignment used in the assessment of control, and demonstration of the accuracy of the video-based method against the 'gold standard' for motion capture. A group of healthy adults was used in this preliminary study to eliminate the complications associated with compromised motor control in children with CP and ensure system accuracy. The application to children with CP provides one example of the general relevance of this concept and method to the overall objective.

[41] Refer to Chapter V, 'Open and Closed Controlled Kinetic Chains', for a detailed description of the components that demonstrate active neuromuscular control.
[42] This study will be referred to as 'Alignment Study' in the other Chapters.

2. Background

The ability to maintain a vertically aligned posture of the head and trunk is fundamental to activities such as sitting or standing and requires good neuromuscular control for its achievement. Deviations from a vertically aligned posture are generally used to understand an imbalance of the musculoskeletal system, but can also indicate an alteration of motor control in neuromotor disability such as cerebral palsy (CP). CP is a neurodevelopmental condition beginning in early childhood and persisting through the lifespan[43]. It is characterised by a disorder of movement and posture due to non-progressive brain damage; poor motor control of the head and trunk is a common feature [5, 10, 11]. In the presence of CP, as an example of a neuromotor disability, poor coordination of the stabiliser muscles of the head, neck and trunk results in an inability to vertically align the body parts and overcome the collapsing effect of gravity. A child, attempting to increase stability, will reduce the degrees of freedom of the vertical column (internal component of a Closed Controlled Kinetic Chain) or use external support to maintain the upright posture (external component of a Closed Controlled Kinetic Chain)[44].

The Introduction above highlighted the limitations of considering the trunk as a single unit. The clinical test that provides the most detailed assessment of control at different trunk segments is the Segmental Assessment of Trunk Control (SATCo) [29]. The SATCo provides detail of control status of six well defined trunk segments and of free sitting if a child is able to do so. Although the SATCo has good inter- and intra-rater reliability [29], it remains a subjective assessment in common with visual and other standardised assessments of alignment [138].

This study thus combines the objective assessment of posture using a method that is appropriate for a clinical setting with a clinical test that gives the greatest depth of information about trunk alignment and characteristics. This combination will allow the assessment of the internal component of motor control through the assessment of the posture of the head and trunk.

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[43] Refer to Chapter II for a detailed definition of Cerebral Palsy and of the associated neuromotor impairment.
[44] The concepts of internal and external Closed Controlled Kinetic Chain (Closed-CKC) are fully described in Chapter V.

3. Methods

3.1 Participants

Twelve adults (6 male, 6 female, mean age 27.9±3.5 years, mean height 1.72 m ± 0.08, and weight 71.8 kg ± 11.8) were recruited to the study. All participants were healthy, did not report any fixed bony deformity or other structural problem of the spine, and had a body mass index less than 29 $kg \cdot m^{-2}$. Detailed anthropometric measurements can be found in Table IX-1. All participants gave written informed consent for participation in this study.

All the participants wore tight fitting clothing; men were asked to leave their upper body free of clothing, women were asked to wear a customised vest that had the back removed. A clear view of the back allowed for more accurate palpation and marking of the spinous processes of the relevant vertebrae for Vicon (Vicon Nexus, Oxford, UK) marker placement, and avoided possible artefacts generated by the movement of clothes (Figure IX-1).

Table IX-1 Participants' anthropometric characteristics.

PARTICIPANT	AGE	SEX	HEIGHT (m)	WEIGHT (Kg)	BMI
AD01	29	Male	1.75	82.5	26.93
AD02	31	Male	1.79	74	23.09
AD03	27	Male	1.77	86	27.45
AD04	24	Female	1.66	61	22.13
AD05	28	Male	1.83	75.75	22.19
AD06	32	Female	1.67	53.7	19.14
AD07	24	Female	1.62	64.8	24.60
AD08	25	Male	1.82	96	28.98
AD09	31	Female	1.75	70.9	23.09
AD10	23	Male	1.82	67.3	20.22
AD11	27	Female	1.65	63.25	23.23
AD12	34	Female	1.60	66.9	26.13

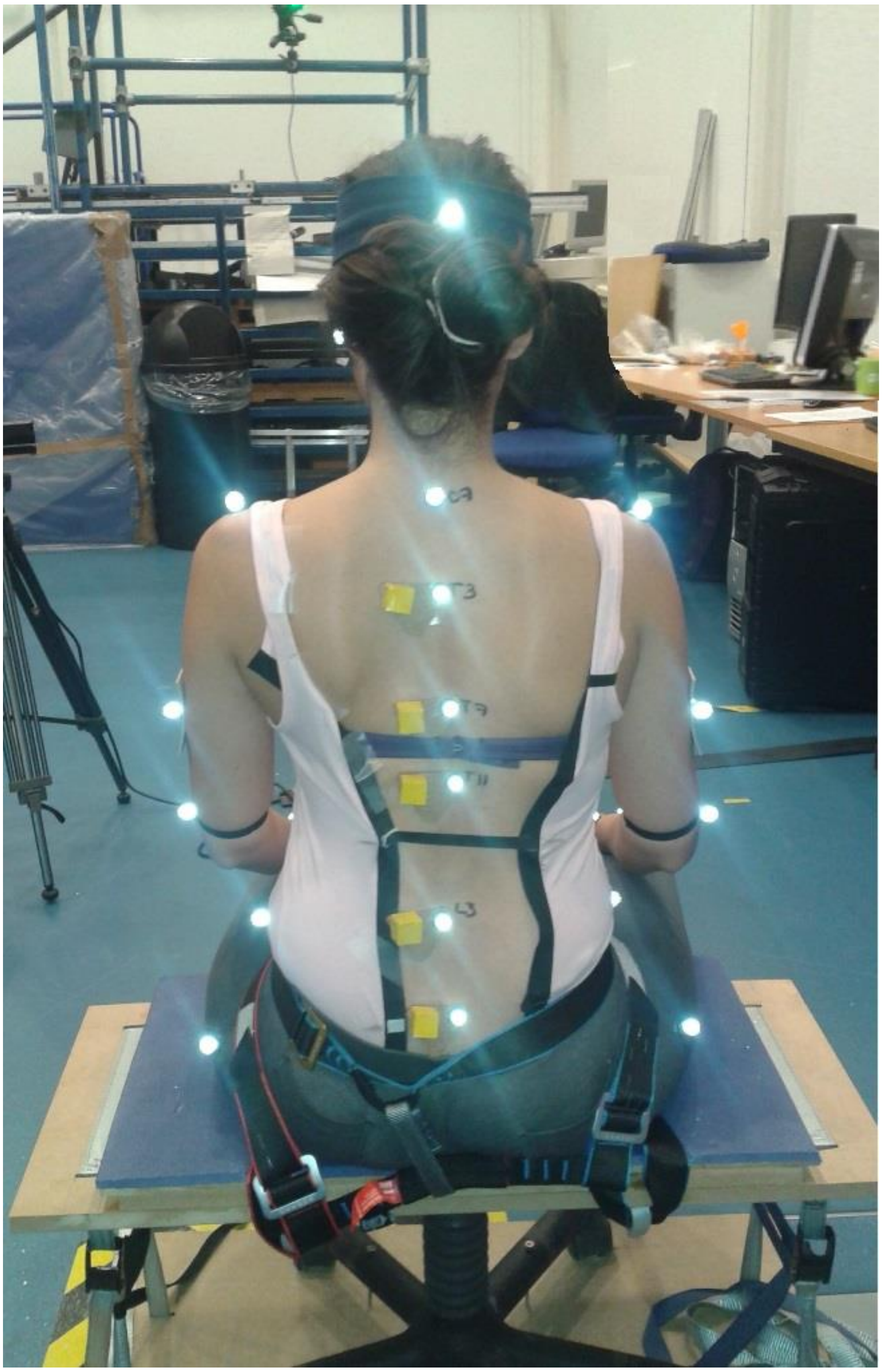


Figure IX-1 View of the back of a participant.

Female participant’s back, showing how the customised vest allowed a clear view of the back.

3.2 Procedures

Participants sat on a bench free of back or arm support. The height of the bench was adjusted to ensure participants' feet were flat on the floor and the knees and hips were flexed at 90°. Participants were instructed that the initial trial position was with the hands in the air at shoulder height with elbows extended; this is a common posture used to assess trunk control in children with cerebral palsy. Data recording began before the hands were lifted to the trial position and ended when the hands were placed down again. This ensured that there were no missing data, and that only the data collected with hands in the trial position were analysed.

Participants were asked to sit upright, and verbal and manual feedback was given to achieve an initial aligned posture in sitting. Two different trials were collected, static and dynamic, to replicate physical therapy tests of control. For the static trials, participants were asked to remain still for 10 seconds in upright sitting with the hands in the trial position (Figure IX-2 A). For the dynamic trials, participants were asked to flex, side-flex or extend their head and trunk (Figure IX-2 B-D), returning to upright sitting after a couple of seconds and between each directional movement. This dynamic component enabled video quantification to identify deviation from the aligned posture. Lateral movements were included to represent the clinical situation more fully.

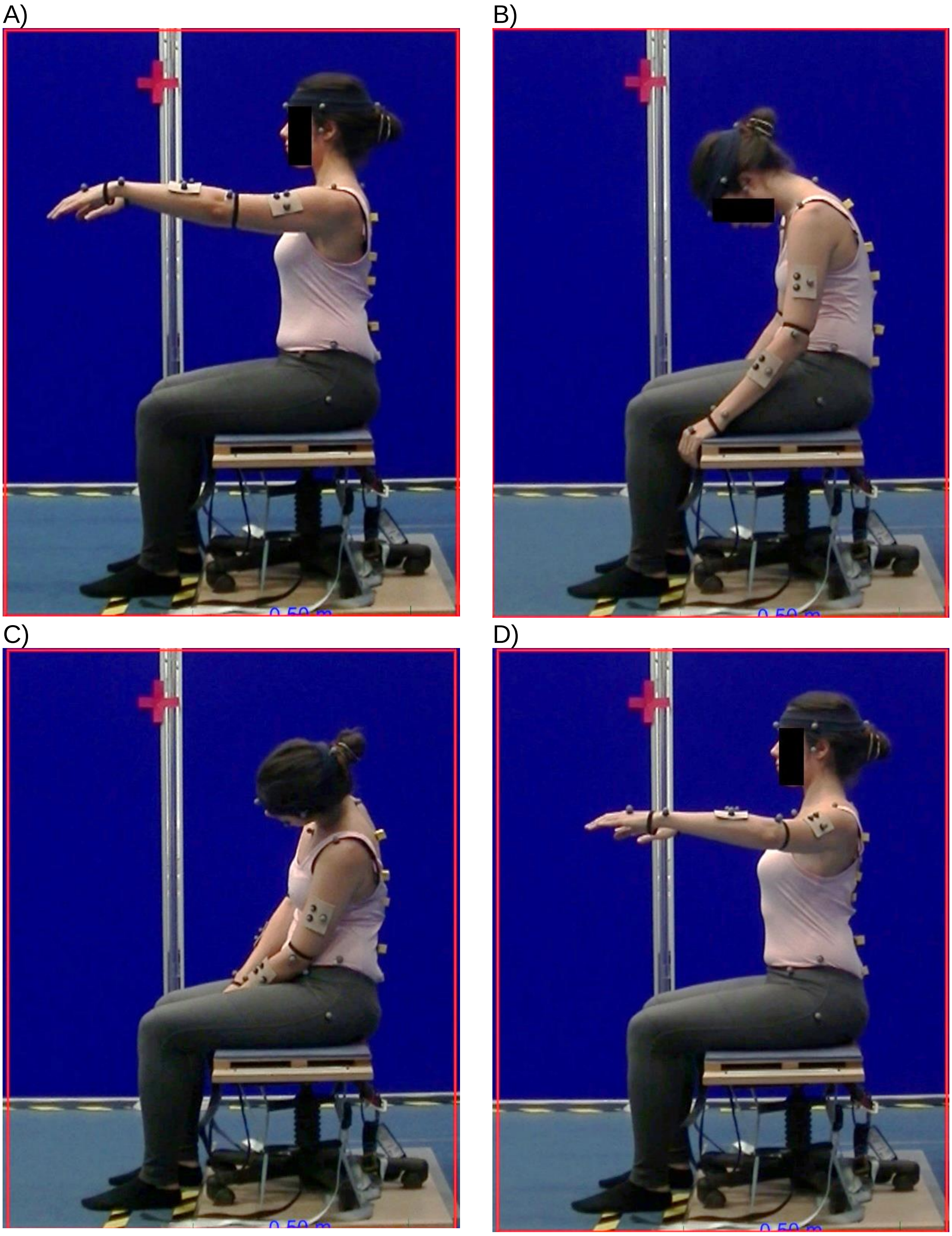


Figure IX-2 Example of positions of the Static and the Dynamic trials.

Pictures showing the posture during A) Static trial and B-D) Dynamic trials. B) Flexion of the head and trunk, C) side-flexion of the head and trunk and D) extension of the trunk

3.3 Apparatus and Measurements

Data were collected simultaneously using a 3D motion capture system and one video camera recording sagittal plane movements.

3.3.1 3D Motion Capture

Motion data was collected using a ten-camera system (Vicon) following the methods described in Chapter VIII (Section 3.3.2). Reflective markers were used to define eight segments (Figure IX-3): Head, Neck, Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Pelvis (Table IX-2). An additional marker on the left elbow was used to identify the trial position of the arm. Marker location and segment definition were based on the description of the SATCo trunk segments [29].

Marker reconstruction and gap filling was performed using Vicon-Nexus software (version 1.8.5). Processing and segmental angles calculation was performed using Visual 3D as described in Chapter VIII, Section 3.4 and Section 4.2.1. A segmental angle was defined as the angle between a given segment and the absolute coordinate system and was calculated for each of the segments defined. Only the sagittal component of the segmental angles was taken into consideration. Data was exported to MATLAB for further analysis.

3.3.2 Video Recording

One video camera mounted on a levelled tripod was placed on the left side of the participant; details about the camera positioning can be found in Chapter VIII (Section 2.2). Small coloured blocks (2x2x2cm) were used to improve the lateral visualization and tracking of the back landmarks (Figure IX-3). The blocks were placed 1.5cm to the left of the equivalent reflective marker. Some of the reflective markers were also used for video tracking.

The same operator processed all videos to obtain coordinates of landmarks from video were obtained using the Dartfish marker tracking tool. A detailed description of this process can be found in Chapter VIII, Section 2.3. Trunk segments creation and segmental angles estimation within the sagittal plane was done using a customised MATLAB, as previously described in Chapter ‘Methods’ Section 4.2.

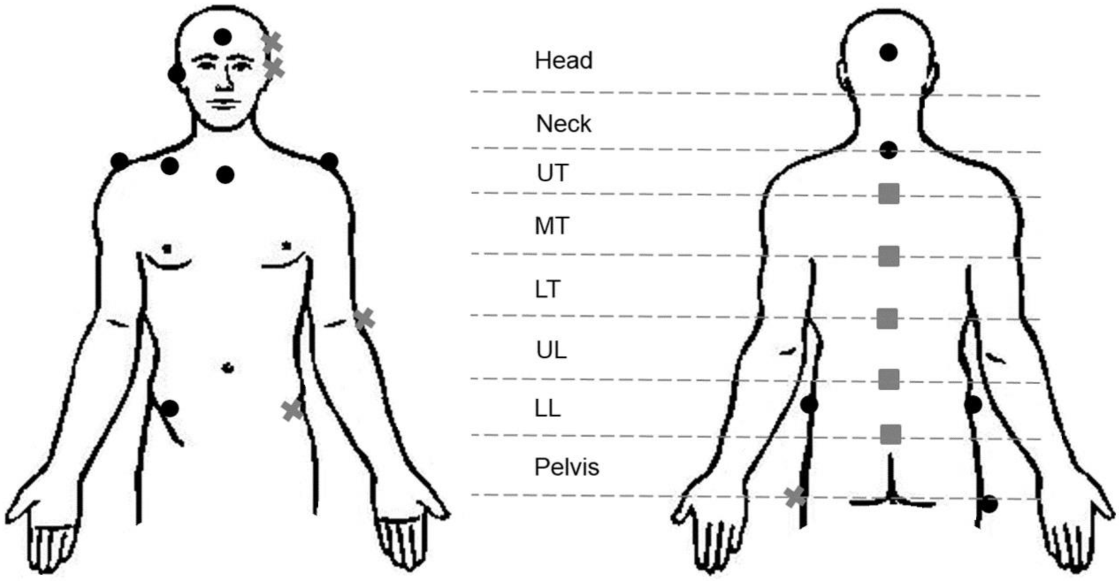


Figure IX-3 Marker locations and limits of trunk segments.

Dots show Vicon marker locations: forehead, occipital protuberance, right ear tragus, clavicular notch, middle of the right clavicle, acromion process of the scapula (right and left), spinous process seventh cervical vertebra (C7), iliac crest (left and right), and right anterior superior iliac spine and greater trochanter. Crosses show reflective markers used additionally for Video tracking: left ear tragus, left temporal fossa (in a vertical line from the ear tragus when the head was in neutral position), left anterior superior iliac spine and greater trochanter. Squares show reflective markers that had an equivalent coloured block: spinous process of the third, seventh and eleventh thoracic vertebrae (T3, T7 and T11), third lumbar vertebra (L3) and first sacral vertebra (S1).

Table IX-2 Marker location for segment definition.

SEGMENT	Marker Location For 3DSegment Definition
Head	Defined by the volume generated by the middle of the forehead, external occipital protuberance, left and right ear tragus and left temporal fossa markers.
Neck	Left ear to
Upper-Thoracic (UT)	Defined between the C7 and T3 markers.
Mid-Thoracic (MT)	Defined between the T3 and T7 markers.
Lower-Thoracic (LT)	Defined between the T7 and T11 markers
Upper-Lumbar (UL)	Defined between the T11 and L3 makers
Lower-Lumbar (LL)	Defined between the L3 and S1 markers.
Pelvis	Defined by the volume generated by the S1, left and right iliac crest, anterior superior iliac spines and greater trochanter markers.

3.4 Data Processing and Analysis

Data processing and analysis for this study has been described in Chapter 'Methods' (Section 4.2.1). The Vicon and the video signal were synchronised prior to analysis. For both systems, positive segmental angles represented anterior inclination relative to the vertical, and detrended and absolute angles were calculated. The detrended angles (D) showed each angle relative to the mean angle for that trial. The absolute angles (A) for all trials were calculated relative to a single value of aligned angle defined by the participant model of alignment (see below). D angles revealed movement of segments within the trial while excluding drift in position between trials. A angles revealed position relative to the vertically aligned posture which remained true for the entire session.

3.4.1 Alignment Model

The definition of postural alignment in sitting was consolidated in a focus group consisting of four physical therapists, each with 5 to 20 years of experience performing SATCo and using their standard working practice definition. The model of alignment was then constructed based on this agreed definition, which is summarised in Figure IX-4. Independent models of alignment were created using the segmental angles calculated for both methods in conjunction with the provided frame numbers where the participant's posture was aligned. For both separate methods, the segmental angles of those frames were then used to calculate the aligned posture based on the information of each separate clinician. For each session, the participant's model of alignment was created, as the mean (± standard deviation) of the aligned segmental angles of each clinician's model.

To validate this frame identification process, inter-assessor reliability was tested using a two-way mixed, absolute, average measures intraclass correlation coefficient (ICC 3,1), and calculated as a collective mean SD per segment. For each assessor, intra-assessor reliability was calculated and is presented as the mean SD values of the identified aligned segmental angles.

3.4.2 *Dartfish Operator Reliability*

Validation of the processing steps was required since Dartfish had not previously been used as a clinically-based video method where coordinates of several markers were extracted to later create segments. The Dartfish operator (DF-operator) reliability was thus calculated using the SD between trials. Twelve trials were processed three times with at least 36 hours between each processing and segmental angles were calculated. As described in Chapter VIII, the processing in Dartfish implied the selection of a specific marker, the adjustment of the parameters to track and the correction of the path in case of visual obstruction. For each set of trials, SD was calculated as a measure of variation and the median value per segment identified.

3.4.3 *Video System Validation*

A key element in the generation of new assessment methods includes their validation against 'gold standard' technologies. In the present study, the validation of the clinically-based video method was defined as the relative agreement between the segmental angles calculated from Dartfish coordinates and the segmental angles from Vicon. Disagreement was calculated as the root mean square error (RMSE) between the signals. RMSE was calculated for D and A angles.

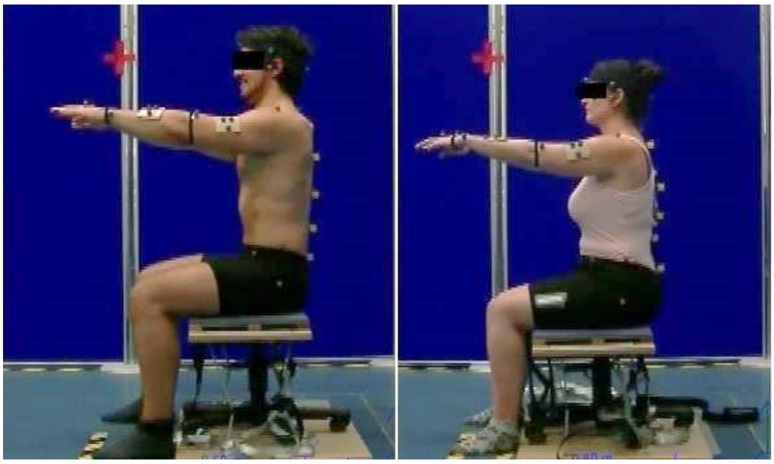
	DESCRIPTION
Head and neck	Chin: Neither protracted nor retracted
	Eyes: Looking forward
	Ear (tragus): Aligned with the hip
Shoulder	Shoulder girdle: Neither protracted nor retracted
Trunk	Smooth and continuous spinal curvatures Thoracic spine: Near flat as possible Lumbar spine: Slight lordosis or flat
Pelvis	Neutral
Lower limbs	Hip – Knee angles: 90º - 90º
Example	

Figure IX-4 Aligned static sitting posture.

Qualitative description of the aligned static sitting posture agreed in the focus group and two examples of aligned posture in sitting.

4. Results

4.1 Alignment Model

The aligned posture for each participant was quantified in Vicon and Dartfish. Dartfish values are presented in Table IX-3; an example of alignment for the 3D model is presented in Figure IX-5. Inter-assessor reliability was excellent for all the segments, ICC=0.99 with 95% CI (0.99, 0.99) for both systems (Table IX-4). Mean SD values for the intra-assessor reliability ranged between 2.1° to 11.6°. Combining all participants, intra-assessor variation had greatest values for the Neck and smallest for the UL segment (Table IX-4).

Figure IX-6 presents the sagittal aligned mean angles and range of the Head, Neck and Trunk segments of the group of 12 healthy adults. This model is based on video data only as it is a clear illustration of the proposed new method and is visually comparable to the clinical view of a participant. The combined model of the quantified aligned sitting posture of this group of adults is presented here as reference; the individual model of alignment of each participant was used for segmental tracking and following validation of the clinical video system.

4.2 Dartfish Operator Reliability

DF-operator reliability varied between 0.86°±0.4 and 2.13°±0.7 for all segments. Table IX-4 shows little variation between segments with least reliability for the Head segment.

Table IX-3 Aligned posture per participant.

Showing the value of the aligned mean angle in degrees (°) and the standard deviation (in brackets) of each segment per participant from the video based clinical system.

Participant	Head	Neck	UT	MT	LT	UL	LL	Pelvis
AD01	11.95° (4.9)	51.41° (2.1)	34.57° (2.0)	7.10° (1.6)	-0.19° (1.1)	-2.83° (0.6)	-0.93° (3.8)	35.52° (8.2)
AD02	4.62° (2.1)	47.60° (2.8)	43.16° (2.2)	12.46° (2.2)	-6.23° (1.6)	-6.58° (0.2)	0.15° (1.6)	19.99° (2.0)
AD03	3.38° (4.9)	42.29° (4.3)	37.94° (1.4)	12.62° (3.8)	-2.40° (1.6)	-4.16° (2.0)	-1.62° (2.3)	42.86° (1.5)
AD04	10.13° (1.6)	54.84° (8.0)	33.01° (3.5)	14.43° (4.4)	6.74° (3.4)	-4.07° (1.6)	16.86° (2.2)	44.62° (0.0)
AD05	-10.00° (2.2)	39.97° (0.7)	36.45° (1.2)	15.39° (1.3)	0.85° (0.9)	-9.01° (0.8)	-2.49° (0.2)	29.51° (0.6)
AD06	18.53° (3.0)	53.56° (1.6)	26.65° (0.3)	15.68° (0.5)	-9.44° (0.7)	-7.33° (0.5)	6.84° (0.8)	18.04° (0.4)
AD07	-3.59° (1.2)	43.99° (1.4)	31.73° (3.4)	9.53° (3.6)	2.17° (2.5)	2.05° (0.9)	4.33° (2.1)	36.50° (2.2)
AD08	9.73° (2.8)	51.77° (1.8)	34.00° (0.4)	5.58° (1.9)	-1.94° (0.6)	-7.80° (0.2)	1.65° (0.5)	27.05° (0.1)
AD09	-2.36° (1.1)	38.60° (1.5)	19.77° (0.6)	3.89° (1.0)	-13.09° (0.4)	-5.54° (0.2)	6.21° (1.5)	37.04° (0.1)
AD10	-1.87° (0.6)	40.87° (1.7)	31.34° (0.5)	13.72° (0.9)	-4.21° (0.4)	-11.31° (2.3)	0.84° (2.1)	31.50° (2.0)
AD11	10.14° (2.5)	45.07° (2.9)	24.24° (1.6)	5.11° (2.5)	-1.88° (0.8)	3.42° (0.4)	11.37° (2.1)	34.67° (1.2)
AD12	1.37° (1.7)	50.18° (4.3)	31.72° (2.0)	17.74° (2.3)	2.09° (1.1)	-5.24° (1.2)	12.06° (0.9)	33.31° (1.4)
Mean	**4.33° (5.9)**	**46.67 ° (5.6)**	**32.04 ° (5.4)**	**11.10° (4.7)**	**-2.29° (5.4)**	**-4.86° (4.2)**	**4.60° (6.1)**	**32.55° (8.0)**

Table IX-4 Showing Dartfish operator reliability mean and SD values per segment in degrees.

Inter-assessor reliability presented as ICC per segment, and as absolute values presented in degrees. The absolute values are the standard deviation of five assessors' mean aligned values. This is the average from all participants. Intra-assessor reliability presented as the mean SD values in degrees for all participants. Calculated agreement between Dartfish and Vicon: the average RMSE and SD in degrees per segment for static and dynamic trials.

CALCULATION	ASSESSOR/TRIAL	GENERAL	HEAD	NECK	UT	MT	LT	UL	LL	PELVIS
DF-operator reliability			2.13° (0.7)	0.86° (0.4)	1.51° (0.4)	0.95° (0.4)	1.15° (0.6)	1.11° (0.5)	1.29° (0.3)	1.01° (0.5)
Inter-assessor reliability (Video)		0.99	0.97	0.92	0.98	0.94	0.98	0.98	0.98	0.99
Inter-assessor reliability (Vicon)		0.99	0.93	0.93	0.97	0.95	0.98	0.99	0.99	0.98
Inter-assessor reliability absolute values			2.03°	2.08°	2.14°	1.85°	1.28°	0.85°	1.29°	0.94°
Intra-assessor reliability	1		7.6°	7.1°	4.4°	5.2°	3.4°	2.2°	3.0°	2.1°
	2		9.0°	10.6°	7.4°	8.7°	5.9°	2.8°	4.7°	4.2°
	3		7.0°	6.5°	4.1°	5.2°	3.7°	2.2°	2.9°	2.5°
	4		8.0°	10.9°	6.8°	7.4°	5.4°	2.8°	4.4°	3.1°
	5		9.6°	11.6°	7.5°	8.9°	6.2°	2.9°	4.9°	4.0°
RMSE Absolute	Static		3.76° (2.3)	1.61° (1.6)	3.31° (2.8)	2.85° (1.8)	3.07° (2.1)	2.77° (1.6)	2.54° (1.5)	3.09° (2.3)
RMSE Detrended	Static		1.19° (0.5)	0.37° (0.3)	0.74° (0.3)	0.38° (0.2)	0.35° (0.2)	0.44° (0.4)	0.40° (0.2)	0.28° (0.2)
RMSE Absolute	Dynamic		8.35° (4.6)	5.50° (2.4)	5.90° (2.3)	2.85° (1.1)	2.48° (1.0)	2.22° (0.9)	2.87° (1.1)	3.53° (1.3)
RMSE Detrended	Dynamic		7.90° (4.2)	5.15° (2.3)	5.41° (2.3)	2.51° (1.0)	2.08° (0.9)	1.77° (0.7)	2.49° (1.0)	2.70° (1.0)

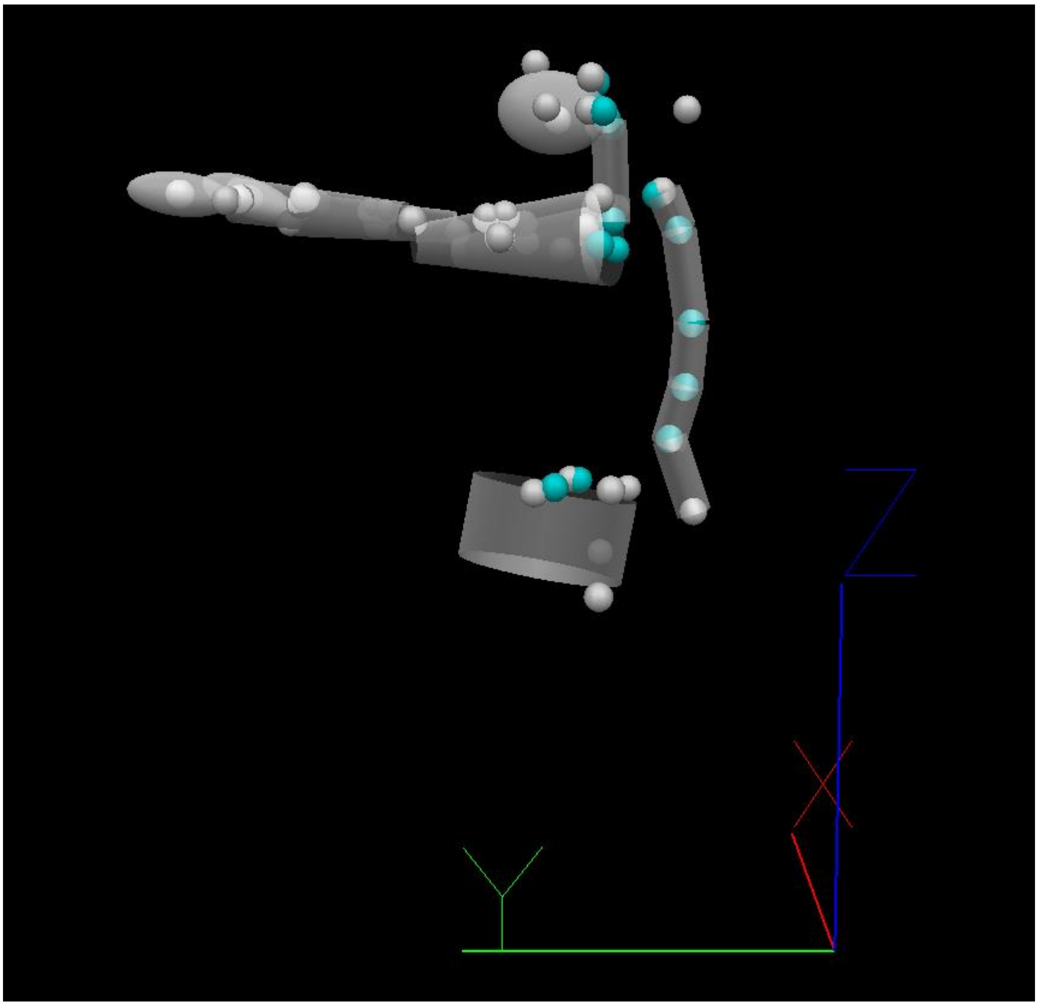


Figure IX-5 Representative example of 3D alignment.

3D representation from a lateral view (Y-Z plane) of an identified aligned frame. Cylinders represent the separate segments on the trunk and pelvis; an ellipse represents the head. Grey and blue spheres represent real and virtual markers used for the reconstruction of the relevant segments.

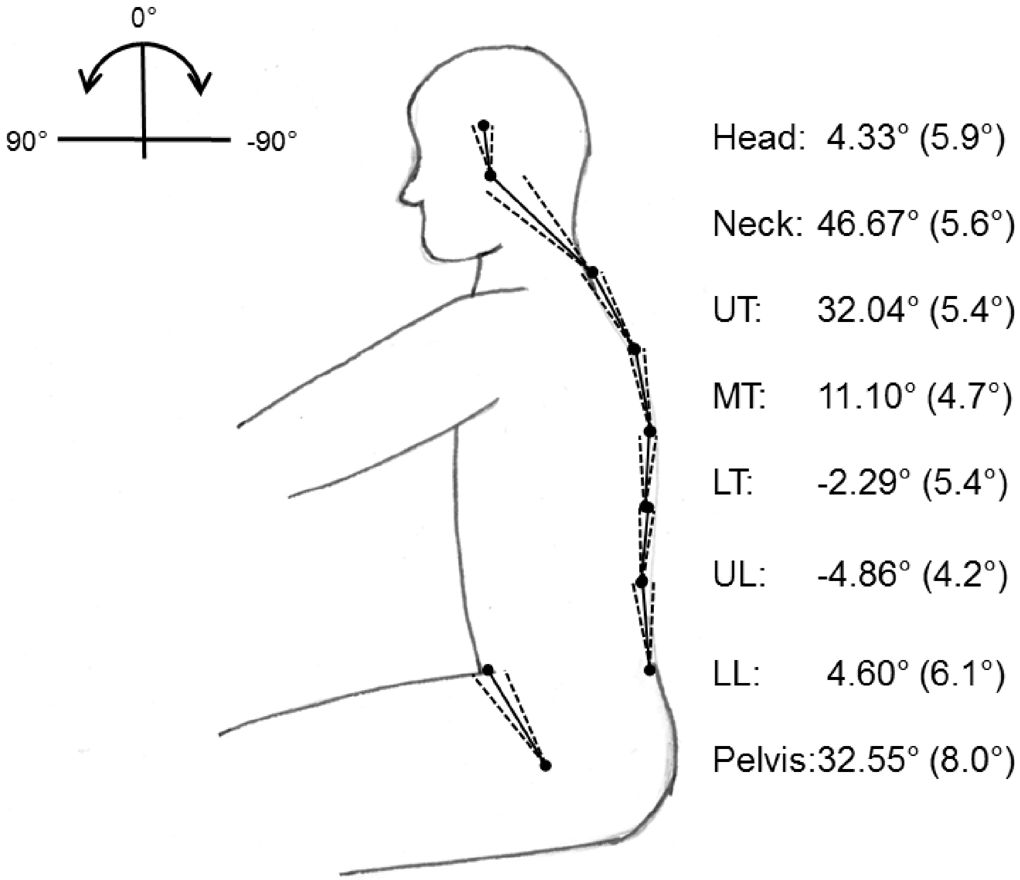


Figure IX-6 Representation of the aligned mean position.

Solid and dashed lines show mean and SD segment orientations respectively from all participants.

4.3 Clinical Video Tracking

Figure IX-7 and Figure IX-8 show a representative example of a static trial and a dynamic trial respectively. For the static trial the variation of the angles relative to the aligned position (0°) is minimum (<1°); this matched the requirements of the trial described above. It can be seen from the dynamic test that the participant moved away from an aligned trunk posture (4-6, 8-10 and 14-16 seconds) and then returned to the initial neutral position. This confirms that video recording can be used to track trunk segments. For the Head, Neck and UT segments there was greater movement than for the LT, UL and LL, which is consistent with the anatomical characteristics[45].

4.4 Video System Validation

Table IX-4 presents the numerical agreement calculated using the root mean square error (RMSE) between the Vicon and Dartfish signals. RMSE for the static trials was below 3° when using the A angles and below 0.5° for the D angles. In both cases the Head and the UT segments showed larger errors (3.76° and 3.31° for A and 1.19° and 0.74° for the D); while the Neck had low errors in both cases (1.61° and 0.37°). The RMSE for the dynamic trials was below 4° for the A and below 3° for the D angles in most cases. The Head and UT had the highest errors (8.35° and 5.9° for A and 7.9° and 5.41° for D). In contrast to the static trials, the calculation of Neck angles in the dynamic trials showed larger errors (5.5° and 5.15° for A and D respectively).

[45] The global flexion-extension, lateral flexion and axial rotation of the spine result from the segmental contribution of the lumbar, thoracic and cervical spine, but it is the cervical spine that has the largest range of motion for the three separate movements [139].

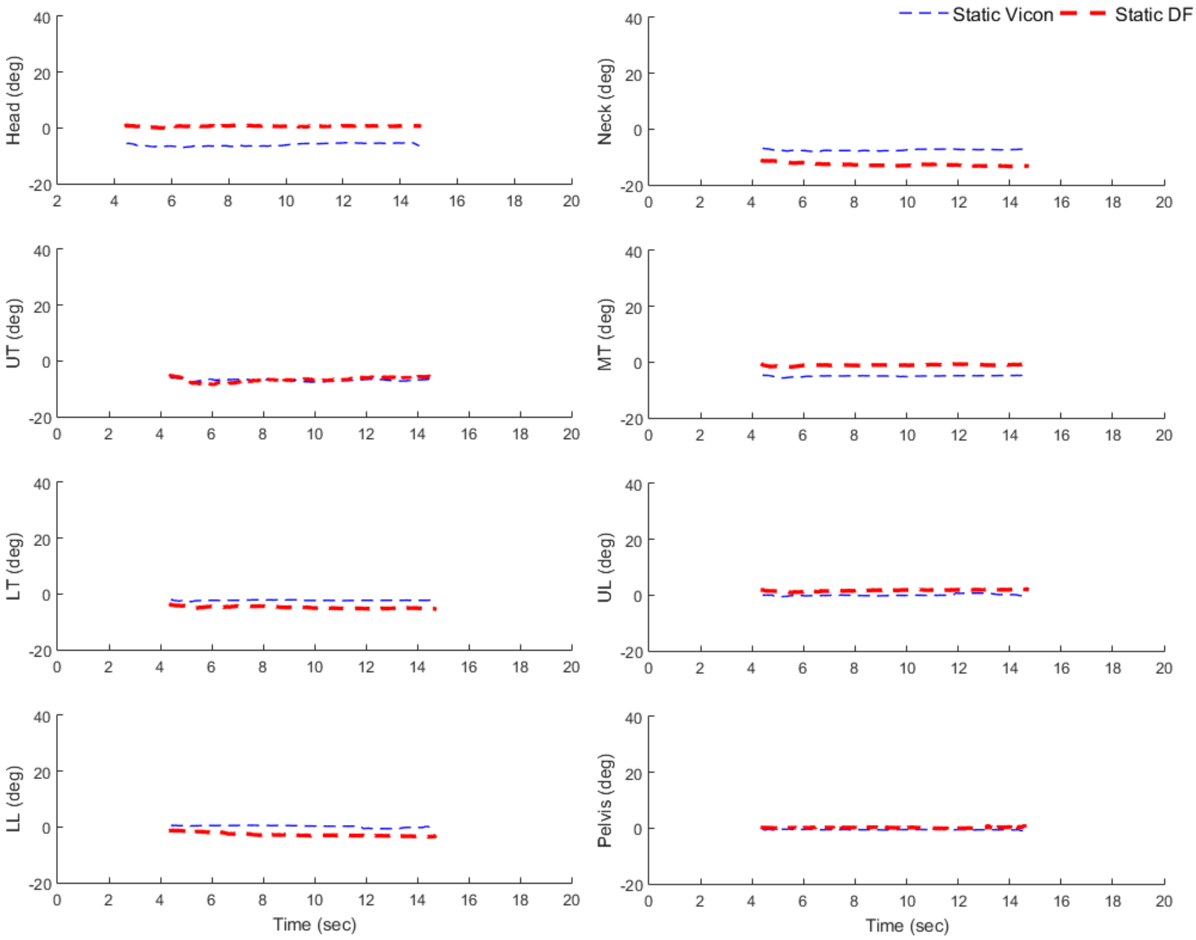


Figure IX-7 Representative agreement between Dartfish and Vicon in a static trial.

Representative example of a time series for segmental absolute angles for a static. Dartfish angles (red) and in Vicon angles (blue) for each segment after the hands reached the trial position. The 0° position corresponds to the aligned angle per segment defined in the aligned model. A positive angle refers to flexion and a negative to extension from the aligned angle.

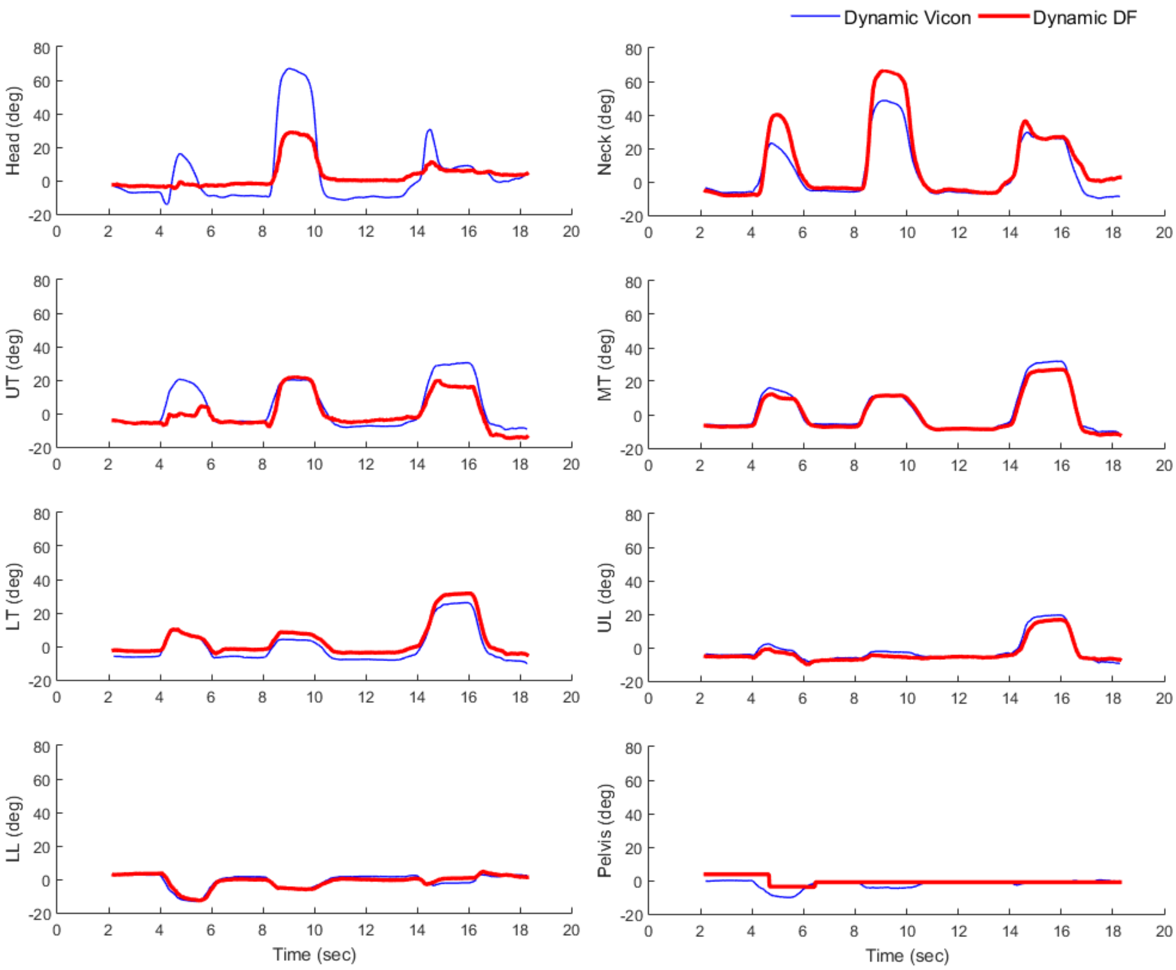


Figure IX-8 Representative agreement between Dartfish and Vicon for a dynamic trial.

Representative example of a time series for segmental absolute angles for a dynamic trial. Dartfish angles (red) and in Vicon angles (blue) for each segment after the hands reached the trial position. The 0° position corresponds to the aligned angle per segment defined in the aligned model. A positive angle refers to flexion and a negative to extension from the aligned angle.

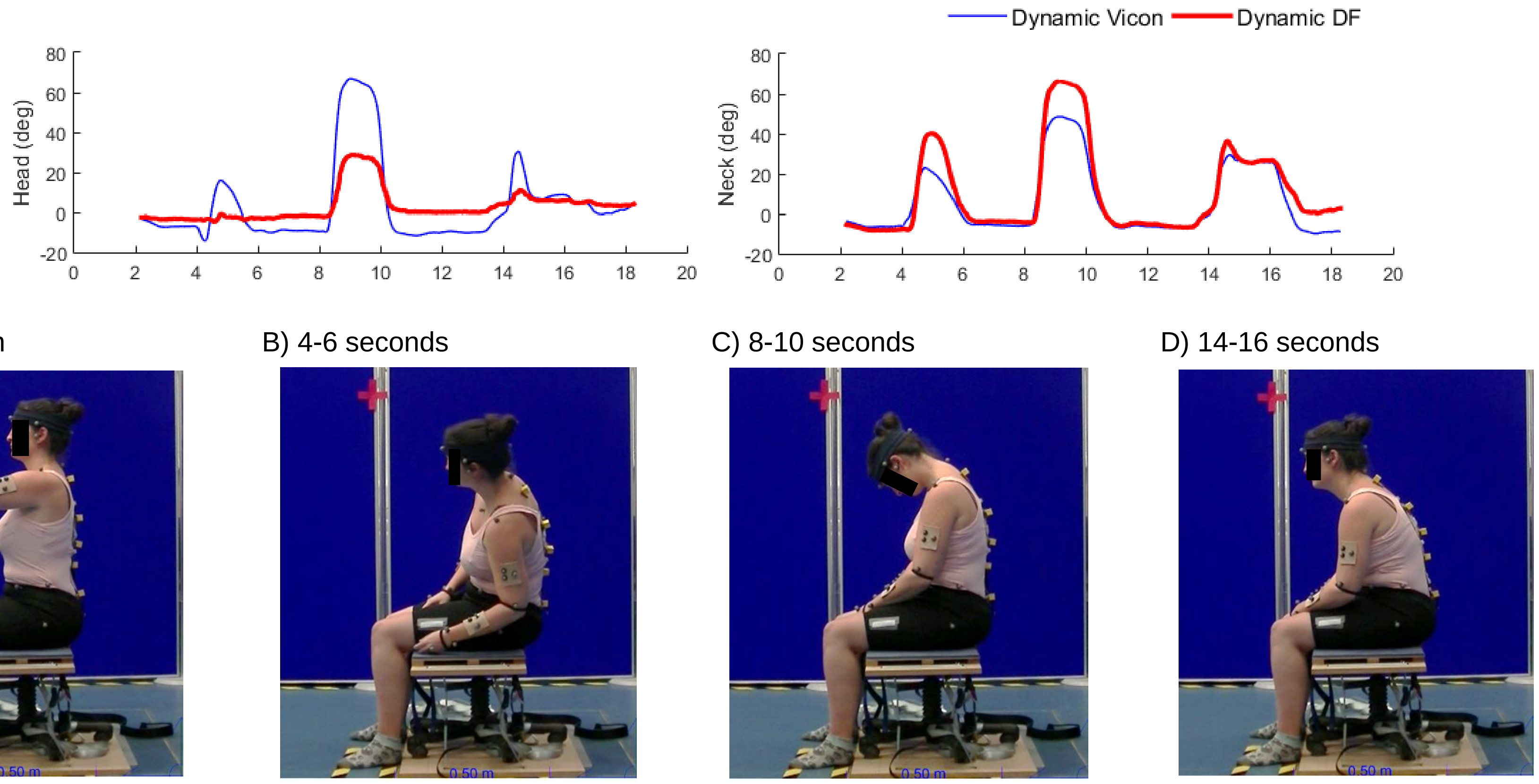


Figure IX-9 Example of the agreement between Dartfish and Vicon for a dynamic trial for the Head and Neck segments with the participant's movements.

Representative example of a time series for segmental absolute angles for the Head and Neck segments for a dynamic trial and the related participant's movements (A-D). Dartfish angles (red) and in Vicon angles (blue) The 0° position corresponds to the aligned angle per segment defined in the aligned model.

5. Discussion

Assessment of alignment in sitting is one of the fundamental components in the evaluation of neuromotor control. This study presents a video-based method to objectively quantify aligned sitting posture and represents an innovative solution in the assessment of motor control that overcomes many of the potential constraints to quantification of alignment in a physiotherapy practice.

This study includes a definition of seated postural alignment and the validation of a multi-segmental numerical measurement of the head and trunk against the gold standard system for motion analysis for both the maintained aligned posture (static) and for the deviation from alignment (dynamic). A numerical illustration of the aligned posture summarising all participants is presented in Figure IX-6.

Previous studies have quantified posture using photographs [77, 140, 141], radiographs [71-73], rastersterography [86, 88, 89] and three-dimensional (3D) motion capture systems [96-98, 114]; most of these have value and application in research, but are rarely practical in a clinical setting. Most 3D motion capture systems usually considered the trunk as a single rigid segment from the iliac crests to the shoulders [97, 114], or the trunk posture is described using a general trunk angle, a cervicothoracic angle and a lumbar angle [71-73, 140, 141]. The limitations of such approaches are confirmed in this study by the revealed detail of the spinal profile from the calculation of separate segmental angles for the thoracic and lumbar region. This detail can be a determinant factor in the generation of a universal model of alignment as it allows the consideration of anthropometric differences. Curtis et al. [98] used a multi-segmental model to represent the trunk. Their model was also based on the seated SATCo [29] and the information obtained from the different segments used to evaluate control. Although the authors calculated angles, these were intersegmental angles (i.e. the angle between two adjacent segments) and were used only to calculate segmental sway and not to evaluate postural alignment. Although their approach represents a major step forward, it was conducted on typically developing children using Vicon. It would thus be difficult to translate into the physiotherapy clinic and a patient population of children with severe neurodisability and learning difficulties.

The development of a video-based method suitable for clinical use was achieved using a video analysis system (Dartfish) and a customised code (MATLAB) to track and calculate the angular displacement of the separate segments. This method has the advantage of presenting an outcome measure that is similar to the human observation of posture so that interpretation is closer to the pre-existing assessment processes used in clinical physical therapy practice. Video recorders are commonly used in clinical practice, in contrast to more complex technologies used to measure spinal angles. The videos were used to obtain angle traces that were visually equivalent to those calculated with the 3D motion capture system. Nevertheless, there were some difficulties generated by the software operation and by the inherent characteristics of the video.

The calculation of the error between Dartfish and Vicon was based on two different angle calculations, absolute (A) and detrended (D) angles. Differences between the two systems are larger for the dynamic trials than for the static trials for both A and D angles; this is associated with the plane of motion in which the movements were executed and the differentiation of movements in only the sagittal plane (automatic in Vicon but requiring visual judgement for the videos). For the static trials, the RMSE was under 1.5° for the D angles; this means that, in relation to the real fluctuations of the angles, both systems were similar irrespective of the participant's position. As a consequence, Dartfish can measure change in angle for static trials, but A angle across an entire session is less reliable (e.g. 3.76° for the Head A angle vs 1.19° for the D angle). For static and dynamic trials, the RMSE was generally smaller than the intra-assessor reliability values (Table IX-4).

One of the main limitations of this method is that video processing required a considerable amount of manual interaction; the operator had to actively select the marker at the beginning of the trial and then manually correct the trajectory of the marker as needed. Nevertheless, the DF-operator reliability was smaller than the intra-assessor reliability, reaching values of only 2.13° (Table IX-4). Now that the clinical potential of this video method has been established, further work to automate the posture evaluation process is justifiable to resolve this problem and make it more clinically applicable.

A second limitation of video is the possibility of marker obstruction. This can result, for example, from movement of the participant’s hand in front of a marker. Such obstruction results in a compromise of marker coordinates for the duration of the obstruction. Processing of this period of marker obstruction was achieved by inferring its position based on the position of other markers and anatomical landmarks. This limitation could potentially be overcome by the development of a system based on a markerless approach.

The use of a single plane sagittal video simplifies clinical operation, but introduces a third limitation in the accurate calculation of segmental angles. This limitation implies that translations or rotations in one or both of the coronal and transverse planes, which are commonly present in clinical assessments, will result in movement artefacts which over or underestimated the displacement of a segment. This was found in the Neck and of the Head and UT segments respectively (Figure IX-9 B-C). Furthermore, the position of the markers in relation to the rotation of the segments in planes other than the sagittal plane, could result in discrepancies where for one segment there is an under estimation of the angular displacement, but for another there is an over estimation (Figure IX-9 C). In this case, when the head rotates axially away from the camera, then the antero-posterior linear translation of the Dartfish markers (which reflects flexion of the head) will be reduced by a cosine factor of the axial rotation of the head. The situation is different for the neck segmental angle the axial rotation of the head can result in smaller or larger Dartfish segmental angles in relation to the direction of the head turn: if the head rotates towards facing the camera, the Ear and C7 markers would be more vertically aligned which would result in a underestimation of the Neck angle, and if the head rotates away from the camera it will result in a overestimation of the Neck segmental angle, as shown in Figure IX-9 C. For those movements performed in a true sagittal plane, however, the Dartfish tracking of the markers was close to the Vicon tracking (Figure IX-9 D). Clinicians should be aware of this planar anomaly but the overall value of the quantification of sagittal movement will outweigh this factor. Movements in more than one plane of motion would merit consideration in future work as they would demonstrate complete picture of the strategies adopted to maintain a balanced sitting position.

The use of only sagittal plane videos does introduce some constraint in the quantification of posture. Alteration of posture and/or compensatory movements rarely are limited to the sagittal plane and commonly also involve displacement of body segments in the transverse and/or coronal plane. Thus, assessors are advised to use clinical judgement in the interpretation of the quantitative information obtained and, at present, seek confirmation by qualitative assessment. Although future work can include simultaneous quantification of other planes of motion, the methods described here should be used as a complementary tool for postural assessment.

The methods used in this study validate the use of video recordings for the quantification of clinically identified aligned posture in sitting. This is the first step towards automated quantification of posture for clinical assessment. Although the focus of this current work is sitting posture, there is no reason why the principles and methods should not be applied in the assessment of standing posture. This would be a major advance in postural assessment.

Assessment of aligned posture is the starting point for many neuro-physiotherapy strategies but, to date, could not be quantified in a clinical setting. The work presented here is an essential component for development of this tool for the quantified assessment of segmental trunk control. Furthermore, it provides validation sufficient to justify future development of an automated processing system suitable to be used in a clinical setting. The participants in this study were healthy adults but the experience gained suggests that video recordings will be a practical method for many clinical contexts and could easily be used with patients with a wide age range and varying pathologies such as children with cerebral palsy, adult stroke or other neuromuscular conditions. It does not require active patient co-operation or understanding and is suitable for use in a clinical environment. Continuous recordings of assessments can complement other clinical outcome measures and support the traditional subjective assessment of posture.

6. Conclusion

This study has demonstrated the accuracy of a novel video based method for objective quantification of clinically identified postural alignment of the head and trunk in sitting. These preliminary results provide a basis for future studies. This has shown to be more accurate and reliable than the subjective judgment, with the added merit of giving a numerical value. In addition, the use of a segmental approach gives the advantage of greater detail of the spinal profile. This method thus has potential as a complementary tool alongside subjective assessments for patients with a wide variety of pathologies.

X. Objective Identification of the Upper Limb Component of a Controlled Sitting Posture

1. Introduction

Independent unsupported sitting, with a vertically aligned head and trunk (head-trunk) is a milestone of typical development and requires full motor control of the head-trunk [6]. Reduction or absence of head-trunk control can result from neuromotor disability such as cerebral palsy (CP) with the consequent lack of independent sitting ability leading to functional limitations [6].

The head-trunk is a kinetic chain of segments comprising the head and neck and successive trunk segments to the pelvis. These axial segments branch into the upper limbs. As described in Chapter V the term ‘Controlled Kinetic Chain’ (CKC) denotes the biomechanical chain as a controlled entity and is used in the context of determining the neuromuscular control status of individual joints within that chain [28]. In independent unsupported sitting, full motor control of the whole kinetic chain of the head-trunk and upper limbs is demonstrated only when there is no end of range mechanical support at any axial joints or from external objects other than the primary support surface. This control without mechanical support is termed an Open-CKC [28]. In the trunk, a sitting posture that is, for example, slumped into full lumbar flexion with passive end of range mechanical support from intervertebral ligaments obviates the need for active control; it is termed a Closed-CKC [28]. This closure is assessed clinically by analysis of trunk alignment [29]. Use of the upper limbs or an external object to support the trunk mechanically can also remove the need for active control and is also termed a Closed-CKC [28]. This closure is assessed clinically by observation of the upper limbs in relation to the trunk and external objects. For example, if a person rests one hand on his/her thigh, then this can help maintain a sitting posture in the presence of poor trunk control even if the trunk is apparently aligned.

Assessment of trunk control should thus consider both alignment of the head-trunk segments and use of the upper limbs. Previous chapters have described how, in neuromotor disability such as CP, motor control is usually assessed through comparison with typically developing children and inferring control status from functional activities [18, 20] or through a child's ability to maintain a balanced posture either statically and/or dynamically [25, 26]. The majority of these assessments, however, do not consider either of the components of control, as considered in the present work. In contrast, the Segmental Assessment of Trunk Control (SATCo), uniquely assesses CKC status at six trunk segmental levels and free sitting [29] by looking at the alignment of the head and trunk when the upper limbs are free of external support. Although the SATCo provides greater information about motor control strategies, in common with other clinical tests, it is subjective. Objective quantification is desirable since it is repeatable, eliminates variability between and within assessors and offers the potential for quantifying clinical changes over time. In order to complement a clinical assessment, an objective automated system should incorporate the rules existing in the specific clinical test. It should also be practical for clinical use and thus 'clinically-friendly' for both for the child and the therapist.

A method for quantifying postural alignment in sitting has been described in Chapter IX 'Alignment Study'. An understanding of the potential of a 3D motion capture system and of a 2D-video-based method to replicate the clinical judgement for the assessment of the upper limb kinetic chain status is essential in the development of an objective method to complement the quantification of postural alignment and thus complete the assessment of head and trunk control in sitting. The aim of the study reported here[46] was to explore the potential for an objective method to establish use of the upper limb component of the CKC following the principles of the SATCo. This was achieved by: i) defining the clinical rules to assess the upper limb kinetic chain status through video recordings; ii) formulating a method to replicate the clinical rules with quantities that could be measured and classified objectively; and iii) testing the extent to which the objective method replicates the clinical judgement.

In the present study, the initial development of the methods was performed with a group of healthy adults to eliminate the complications associated with

[46] This study will be referred to as 'Upper Limb Study' in the other Chapters.

compromised motor control and enabling a clearer understanding of how the objective methods replicated the clinical rules. The results presented in this Chapter were based on trials where the participant had an aligned posture of the head and trunk; thus all references to (external mechanical) support relate only to determination of the presence or absence of a Closed-CKC or an Open-CKC. The adult analysis was based on 3D motion analysis (Vicon) and 2D-video data (Dartfish), and included the separate analysis of different arm positions that simulated the provision of external mechanical support by the arms as children with poor head and trunk control might do, or positions where the upper limbs were not providing support. The 3D motion analysis method developed was then tested in a real clinical context with a group of children with CP, allowing understanding of the extent to which the methods replicated the clinical judgement.

2. Methods

2.1 Participants

Two groups of participants were recruited: an adult group (Adult-group) of 3 males, 2 females, mean age 28 ±4 years, mean height 1.72m ±0.09, and weight 73.1kg ±10.2 tested at MMU; and a child group (Child-group) of 4 males, 1 female, mean age 8.4 ±4.62 years, mean height 1.1m ±0.27 and weight 24.16kg ±10.8 tested at The Movement Centre (TMC, Oswestry, Shropshire, United Kingdom). All adults were healthy with a body mass index <29 $kg \cdot m^{-2}$ (Table X-1). All children had a diagnosis of cerebral palsy and were participating in Targeted Training (TT) therapy at TMC. All adults gave written informed consent for their participation. Children's parents provided written informed consent with child assent where possible. To allow accurate palpation of anatomical landmarks for marker placement, adults wore a tight pair of shorts with men leaving their upper body free of clothing and women wearing a tight vest. Children wore only their underwear, nappy or shorts as usual for their clinical assessments.

2.2 Procedures

All participants sat in an upright aligned posture on a bench free of back or arm support. The height of the bench was adjusted to ensure each participant's feet were flat on the floor with knees and hips flexed at 90°. Adults performed a sequence of twelve arm movements that represented both Open-CKC as in positions that gave no external mechanical support, such as both arms in the air to the sides or the front, and Closed-CKC where the arms were providing external mechanical support/contact, such as hands on the bench, legs or head (Table X-2). Six trials were recorded per participant with different segmental levels of trunk control tested (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS) following the SATCo guidelines [29]. An assistant provided manual support to the trunk directly beneath the tested segment resulting in 'unsupported segments' above the manual support: arms (tip of the fingers to axillae), head and unsupported segments of the trunk. This is the standard SATCo test procedure for testing of each trunk segment in turn.

Children were recorded during the routine SATCo performed as part of their TT therapy.

Table X-1 Participants' anthropometric characteristics.

	PARTICIPANT	AGE	SEX	HEIGHT (m)	WEIGHT (Kg)	BMI
Adult-group	AD01	29	Male	1.75	82.5	26.93
	AD03	27	Male	1.77	86	27.45
	AD10	23	Male	1.82	67.3	20.22
	AD11	27	Female	1.65	63.25	23.23
	AD12	34	Female	1.60	66.9	26.13
Child-group	TMC11	11	Female	1.26	29.3	18.46
	TMC08	5	Male	0.89	13.5	17.04
	TMC15	12	Male	1.37	36	19.18
	TMC06	2	Male	0.82	11.7	17.40
	TMC10	12	Male	1.38	30.3	15.91

Table X-2 Sequence of arm movement, representing support and no-support positions.

Position	Instruction	Chain Status
1	Start trial position	Open-CKC / No-Support
2	Hands on the lap	Closed-CKC / Support
3	Hands held in the air, keeping them level with the ears, and maintaining the elbows at a right angle.	Open-CKC / No-Support
4	Hands resting on the bench.	Closed-CKC / Support
5	Hands away from the bench.	Open-CKC / No-Support
6	Elbows tucked in the waist and hands to the sides as far as possible.	Closed-CKC / Support
7	Elbows away from the waist. Hands away from the sides	Open-CKC / No-Support
8	Hands on the head.	Closed-CKC / Support
9	One arm up and to one side and the other arm down and to the other side thus forming a diagonal line with the arms.	Open-CKC / No-Support
10	Finger tips in the mouth.	Closed-CKC / Support
11	Both arms stretched out to the sides, shoulders abducted (~90°) and elbows extended.	Open-CKC / No-Support
12	Both hands pressed to each other in front of the chest with the elbows in the air.	Closed-CKC / Support

2.3 Apparatus and measurements

Data were collected simultaneously using a 3D motion capture system and one video camera.

2.3.1 3D Motion Capture

Motion data was collected using a ten-camera system (Vicon) following the methods described in Chapter VIII (Section 3.3.2). Reflective markers were used to define the Head, Trunk and Pelvis segments, and to track the position of the right and left Elbow and Hand (Figure X-1). Hands and Elbows were selected as representative upper limb landmarks.

Marker reconstruction and gap filling used Vicon-Nexus software[47]. Processing was performed using Visual 3D as described in Chapter VIII (Section 3.4 and 4.2.3). Data was exported to MATLAB for further analysis.

2.3.2 Video recording

Video was recorded from one video camera mounted on a levelled tripod placed directly in front of the Adult-group; for the Child-group the camera was placed at right diagonal front (approximately 45°) to allow the parent to stand in front of the child and encourage their child to maintain an aligned siting posture while trying to reach a toy in front of them (without touching it) but without obstructing the camera view. Either front or oblique views are permissible for SATCo. A detailed description of the camera's positioning can be found in Chapter VIII (Section 2.2.3).

A second lateral view camera was used to confirm those trials where the head-trunk was vertically aligned and only those trials were processed.

[47] Refer to 'Methods' (Chapter VIII) for details about data processing with Vicon.

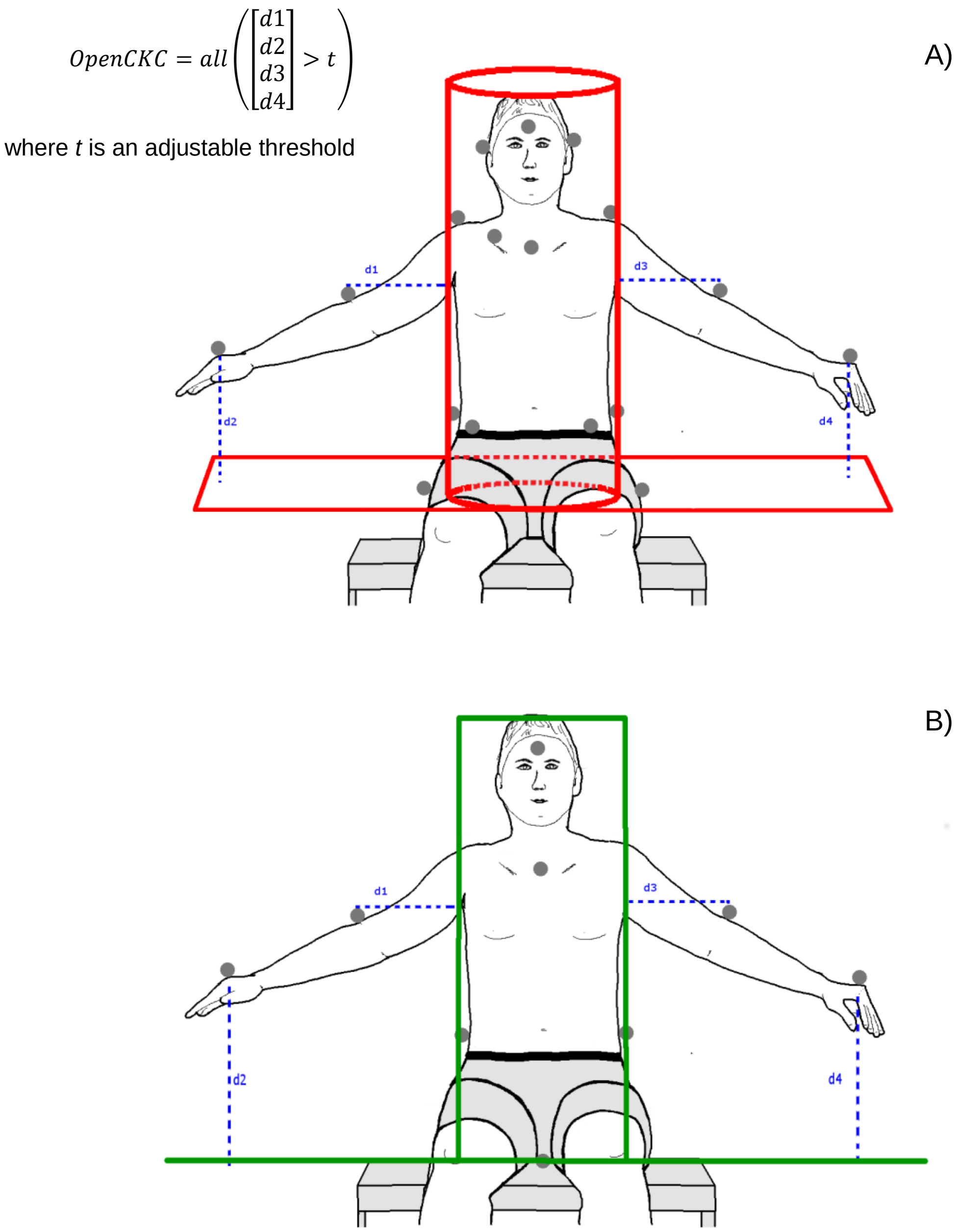


Figure X-1 Marker locations and supported-body.

A) Dots show Vicon marker locations: forehead, middle of the right clavicle, left and right acromion process of the scapula, lateral condyle of the humerus (elbow), head of the third metacarpal bone, Iliac crest, anterior superior iliac spine and greater trochanter. The red cylinder and plane represent the volume that defined a Closed-CKC.

B) Dots show Dartfish marker locations: forehead, lateral condyle of the humerus (elbow), head of the third metacarpal bone, Iliac crest, and superior end of the bench. The green rectangle and line represent the area that defined a Closed-CKC.

Dashed blue lines (A, B) show the shortest distances ($d_{1\text{-}4}$) from each of the hands and elbows to the supported-body surface for this given posture.

2.4 Data processing and analysis

The Vicon and video were synchronised prior to analysis using an initial manual synchronisation followed by automated fine tuning using cross correlation, as described in Chapter VIII (Section 4.2.3).

2.4.1 Clinical identification of Open-CKC

The clinical classification of CKC status was performed by five clinicians familiar with this process (5-20 years of daily use); since trunk alignment was given, this classification was based only on the position of the upper limb. Assessors followed the rule: a Controlled Kinetic Chain is open when there is no contact between an unsupported segment and any other part of the body or any external objects. ‘Contact’ includes firm and light touch; ‘external objects’ include the supporting bench, toys, parent’s hands and the hands supporting the trunk for the SATCo. Definition and assessment of the aligned posture in sitting has been described elsewhere [29, 142].

Open-CKC frames were identified from both the adult and child videos and frame numbers exported to MATLAB for further analysis. The collective classification of all assessors was calculated by the mode classification for each frame.

Inter-assessor reliability was tested using a two-way mixed, absolute, average measures intraclass correlation coefficient (ICC 3,1) for each group. Intra-assessor reliability was tested for one of the assessors with 49 randomly selected videos from both groups.

2.4.2 Objective identification of Open-CKC.

The objective identification of Open-CKC was based on both 3D motion analysis (Vicon) and 2D-video data (Dartfish) for the Adult-group, and only using Vicon data for the Child-group. Dartfish data in the Adult-group came from the frontal camera which was not practical for the Child-group. The oblique video recordings in the Child-group did not allow obtaining the equivalent data from the frontal camera used in the Adult-group; therefore 2D-videos were used only for clinical identification of Open-CKC.

For the objective (Vicon and Dartfish) classification of Open-CKC the classification rule was simplified to the location of four markers (both hands and both elbows) in relation to the body and supporting bench. For Vicon, the body was represented by a 3D cylindrical volume covering the head-trunk and pelvis, and the bench was defined as the volume below the trochanteric markers (Figure X-1 A). For Dartfish, the body was represented by the rectangular area covering the head-trunk and pelvis, and the bench was defined as the area below the bench marker (Figure X-1 B). The volumes and areas were termed 'supported-body'[48]. The shortest distance from the hands and elbows to the supported-body was calculated by customised MATLAB code (Figure X-2 A, B)[49]. An Open-CKC was present when all distances (both hands and elbows) were > *t* mm, where the threshold (*t*) was an adjustable parameter (Figure X-1, Figure X-2 C, D).

$$OpenCKC = all\left(\begin{bmatrix} d1 \\ d2 \\ d3 \\ d4 \end{bmatrix} > t\right)$$

The threshold (*t*) represented the minimum clearance distance from each hand or elbow to the boundaries of the supported-body for the positive classification of an Open-CKC. Three methods for setting *t*-values were used: i) $t = 0$ (unfitted); ii) adjusting *t* using an optimisation routine to maximise agreement with the collective clinical assessment (fitted); and iii) using generalised fixed values not requiring assessor judgement (fixed-values). For the unfitted method, the clearance distance was defined by the real boundaries of the supported-body; this analysis was required to identify to what extent an Open-CKC could be objectively identified and compared to a clinical identification. For the fitted method, the definition of the minimum clearance distance was optimised for each trial to maximise the agreement with the clinical judgement; this method served to illustrate the modifications required to the threshold values, and the extent to which the objective method matched the clinical judgement. For the fixed-values, the minimum clearance distance was $t > 0$, as in the fitted method, but it was not adjusted on a case to case basis; the generalised threshold values of the fixed-

[48] The term 'supported-body' is used to recognise the support given by the bench and from the assistant's hands around the trunk.
[49] Refer to Methods (Chapter VIII) for more details.

value method, represent an intermediate point between the unfitted and the fitted methods in the identification of Open-CKC, where general threshold values have been pre-defined to favour agreement, without requiring the clinical input for their definition.

2.4.3 Agreement between clinical and objective methods

The agreement between the objective (Vicon and Dartfish) and the collective clinical classification of Open-CKC was calculated as the percentage of time during which the classifications were the same for each trial (Figure X-2 E, F). For comparison, the mean percentage agreement between individual assessor and the collective clinical classification was also calculated.

Statistical difference between processing agreement methods was calculated with a repeated measures ANOVA for each group. The differences between segmental levels for each group was assessed using a univariate analysis for each processing method.

- Open-CKC and Arms Positions

For the Adult-group, agreement was also calculated for the different positions (described in Table X-2) of the arms and hands. The sequence of different arm and hand positions performed by the adults represented a simulation of the strategies that children could use to maintain a balanced sitting posture in the absence of trunk control, and the gestures children might use in an attempt to reach a toy, for example when the parent encourages him/her to reach with both upper limbs free of support.

For the unfitted and fitted methods of assessors v Dartfish and assessors v Vicon, the mean values of agreement were calculated for the positions grouped as No-Support (Open-CKC) and Support (Closed-CKC), and for each separate position.

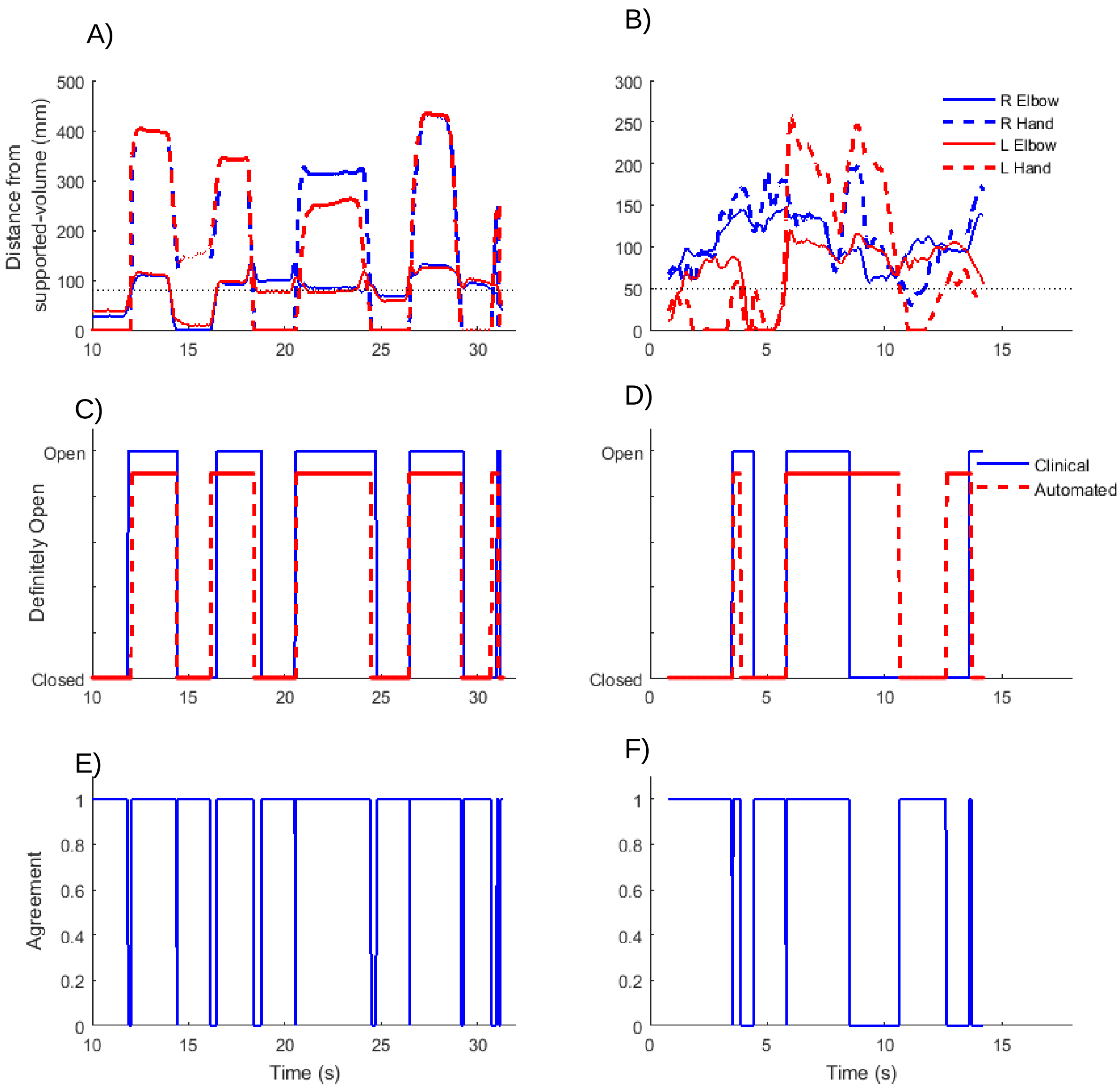


Figure X-2 Representative examples of the objective tracking of the upper limb, classification of Open CKC and calculated agreement over time.

Showing a representative trial example for the Adult-group (panels A,C,E) and Child-group (panels B,D,F). A,B) Objective tracking of the upper limb (left, red line; right, blue line) shows the position of the hands (dash) and elbows (continuous) relative to the supported-body. The black dotted line shows the t-values used for calculations. C,D) Classification of the Open-CKC for the clinical (blue line) and the objective (dash red line, reduced height for visibility) assessment using the fitted method for the adult and the fixed-values method for the child. E,F) Shows the agreement between clinical and objective classification (92.4% for the adult. 68.5% for the child).

3. Results

The objective methods defined in the present study were based on data collected with a 3D motion capture system (Vicon) and on the data obtained from 2D-video recordings of the participant (Dartfish). While the data obtained from a 3D motion capture system allows a spatial reconstruction to understand how the different components of the head-trunk-upper limb kinetic chain interact; the 2D-video data from a frontal view of the participant gives single plane information of how the same segments relate. Interestingly, from 2D-video recordings (frontal or oblique), humans can identify the 3D interaction of the separate segments of the head-trunk-upper limb kinetic chain.

Twenty-nine Adult-group trials and 52 Child-group trials were analysed.

The clinical inter-assessor consistency of Open-CKC identification was excellent for both groups (Adult-group ICC=0.96, Child-group ICC=0.95). Intra-assessor reliability was also excellent (ICC=0.89).

3.1 Adult-group

Adult-group results show how objective methods (3D motion capture and 2D-video analysis) can replicate the clinical rules in the classification of an Open-CKC. For the Adult-group the unfitted, fitted and fixed-values clinical v Vicon agreements calculation were significantly different between methods (68.19% ±15.7, 88.32% ±5.3 and 80.80% ±3.1 mean ±SD respectively for unfitted, fitted and fixed-values) ($F_{2,46}$=127.79 p<0.001). There was significant difference between methods for the clinical v Dartfish agreement calculations (68.63% ±12.0, 84.4% ±8.3, 74.31% ±10.3 as previous) ($F_{2,46}$=82.73, p<0.001) (Figure X-3). Differences between the unfitted, fitted and fixed-values methods showed how it was possible to objectively classify Open-CKC (unfitted); that the agreement could be maximised with the optimisation of a single parameter (t-value, fitted); and that by using a generalised t-value the improved agreement between the clinical and the objective methods no longer depended upon having a clinical assessment (fixed-values) available.

For the Adult-group, the differences between the estimated agreements for the different segmental levels tested were calculated. The unfitted clinical v Vicon and the clinical v Dartfish agreements were significantly different ($p \leq 0.001$) between the UT and all the other segmental levels with a calculated agreement for the UT of 37.25% for Vicon and 44.19% for Dartfish. The fitted processing showed that agreements were significantly different between the UT and MT, LL and FS (both $p<0.05$) for the fitted clinical v Vicon, and between the UT and all the other segments ($p \leq 0.05$) for the clinical v Dartfish agreement calculations; the calculated agreement for the UT increased around 50% for both methods, but the increment was an average of 10% for the other segments. There were no differences for the fixed-values processing for the clinical v Vicon, but for the clinical v Dartfish there were significant differences ($p<0.05$) between the UT and the LT, UL, LL and FS, where the UT agreement calculated was 10% larger than the agreement for the other segments (Figure X-3). Evaluation of this variation in the agreement between the clinical judgement and the objective methods in relation to the segmental level tested revealed that for the UT segmental level the information identified by the assessors is not fully reflected by the objective methods (unfitted), but can be replicated with the modification of a single parameter.

The analysis of the t-value served to further illustrate the modifications required to maximise the agreement between the objective method and the clinical judgement. For the fitted agreement, the optimal t-values are presented in Figure X-4. The Adult-group shows larger t-values for the UT (190.8mm, clinical v Vicon; 209.6mm clinical v Dartfish) and MT (186.6mm and 152.1mm for the clinical v Vicon and v Dartfish respectively) segmental levels. The t-values for the clinical v Dartfish agreement of the lower segmental levels tested (LL and Free Sitting) were smaller than 40mm in contrast with the t-values of the clinical v Vicon for the same levels (t >95mm). This shows that the minimum clearance distance is larger for the UT and the MT segmental levels than for the other levels; this applied to both objective methods.

The t-values information obtained from the clinical v Vicon was used to define the threshold values for the fixed-values agreement at 200mm for UT and MT segments, 100mm for other segments in the Adult-group.

3.1.1 *Arm position agreement*

The sequence of different arm positions performed by the adults was a simulation of arms and hands positions combinations that children could use to either give external support from the upper limbs (Closed-CKC) or a free-of-support situation (Open-CKC). Calculated agreement for the unfitted and fitted methods further illustrate the extent to which the methods replicated the clinical judgement. Overall, the calculated agreement between the clinical classification of Open-CKC and Dartfish or Vicon for the different positions was better for the fitted than for the unfitted method (Figure X-5, Figure X-6).This supports the previous findings of how agreement improves with the modification of a single value.

The results for the UT segmental level described in the previous section are further confirmed by the analysis of the different arm position. For the unfitted method, the UT level of support had agreement values of 44.73% and 46.26% for clinical v Dartfish (No-Support and Support respectively) and of 33.51% and 46.88% for clinical v Vicon (No-Support and Support respectively). This contrasts with the other segments that had values above 65% for both methods and support conditions. This difference was eliminated in the fitted method, where the agreement calculated for No-Support and Support both for clinical v Dartfish and clinical v Vicon was above 80% for all the segmental levels (Figure X-5).

The UT segmental level had the lowest agreement calculated (8.55 – 75%) for the analysis of the separated positions, clinical v Vicon unfitted method, with exception of Position 11 when testing MT (0.62%) (Figure X-6 A). For the clinical v Dartfish (unfitted) the lowest agreement calculations were also found for the UT segment (24.92-75%) (Figure X-6 B). The mean calculated agreement was showed generally lower for positions 11 (both arms stretched out to the sides, shoulders abducted (~90°) and elbows extended) and 12 (both hands pressed to each other)[50] across the segmental levels tested both for Vicon (position 11: 0.62-57.82%, position 12: 29.47-66.36%, Figure X-6 A) and for Dartfish (position 11: 8.87-51.15%, position 12: 24.92-65.15%, Figure X-6 B), in contrast with the other positions.

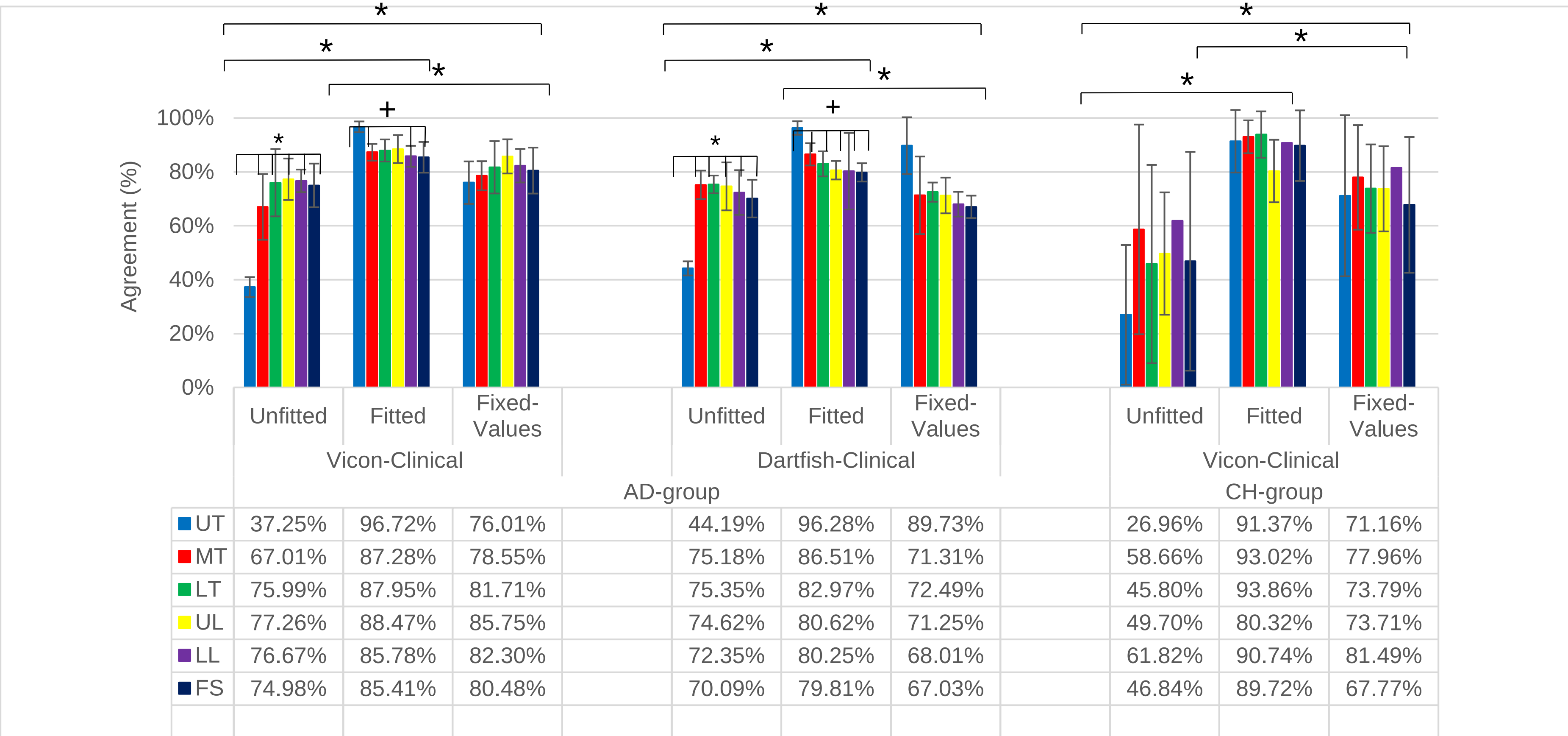
[50] See Table X-2 above for the detailed description of the arm positions.

For the fitted method, the agreement calculated for all the positions was between 60% and 100% for the clinical v Vicon calculations (Figure X-6 C). In contrast, for the clinical v Dartfish the general agreement calculations was between 50% and 100% except for positions 1 and 2 when testing UL (20.42% and 31.97% respectively) and position 4 when testing Free Sitting (53.33%) (Figure X-6 D).

3.2 Child-group

When testing the developed methods in a real clinical context it was seen that for the Child-group the unfitted, fitted and fixed-values clinical v Vicon agreements calculation were significantly different between methods (48.3% ±33.9, 89.84% ±10.2 74.31% ±21.5 respectively ($F_{1.32,92}$=41.07, p<0.001) (Figure X-3). However, there were no significant differences between segmental levels for any of the agreement methods (Figure X-3).

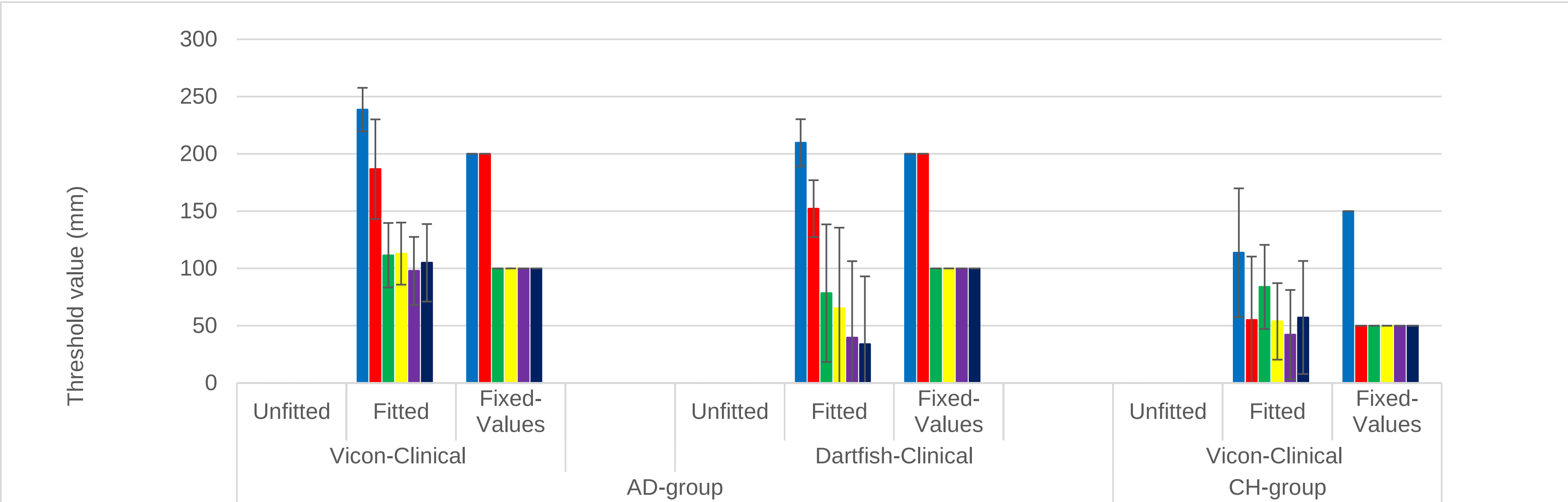
The fitted agreement calculations showed how the optimal *t*-values for the Child-group were larger for the UT (113.7mm) and LT (83.8mm) segmental levels (Figure X-4). This information was used to define the threshold values for the fixed-values agreement at 150mm for the UT segment and 50mm for all other segments.



	AD-group Vicon-Clinical Unfitted	AD-group Vicon-Clinical Fitted	AD-group Vicon-Clinical Fixed-Values	AD-group Dartfish-Clinical Unfitted	AD-group Dartfish-Clinical Fitted	AD-group Dartfish-Clinical Fixed-Values	CH-group Vicon-Clinical Unfitted	CH-group Vicon-Clinical Fitted	CH-group Vicon-Clinical Fixed-Values
UT	37.25%	96.72%	76.01%	44.19%	96.28%	89.73%	26.96%	91.37%	71.16%
MT	67.01%	87.28%	78.55%	75.18%	86.51%	71.31%	58.66%	93.02%	77.96%
LT	75.99%	87.95%	81.71%	75.35%	82.97%	72.49%	45.80%	93.86%	73.79%
UL	77.26%	88.47%	85.75%	74.62%	80.62%	71.25%	49.70%	80.32%	73.71%
LL	76.67%	85.78%	82.30%	72.35%	80.25%	68.01%	61.82%	90.74%	81.49%
FS	74.98%	85.41%	80.48%	70.09%	79.81%	67.03%	46.84%	89.72%	67.77%

Figure X-3 Calculated agreement between the clinical and the objective identification of Open-CKC.

Showing the mean collective percentage of agreement for the Adult-group (AD-group) and the Child-group (CH-group) for all processing methods (unfitted, fitted and fixed) and the standard deviation (error bars). Agreement is presented separately for each segment tested (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS). +indicates significant difference, p<0.05. * indicates strong significant difference, p<0.001.



	AD-group Vicon-Clinical Unfitted	AD-group Vicon-Clinical Fitted	AD-group Vicon-Clinical Fixed-Values		AD-group Dartfish-Clinical Unfitted	AD-group Dartfish-Clinical Fitted	AD-group Dartfish-Clinical Fixed-Values		CH-group Vicon-Clinical Unfitted	CH-group Vicon-Clinical Fitted	CH-group Vicon-Clinical Fixed-Values
UT	0	239	200		0	210	200		0	114	150
MT	0	187	200		0	152	200		0	55	50
LT	0	111	100		0	78	100		0	84	50
UL	0	113	100		0	65	100		0	54	50
LL	0	98	100		0	40	100		0	42	50
FS	0	105	100		0	34	100		0	57	50

Figure X-4 Threshold values.

Showing threshold mean values and the standard deviation (error bars) for the fitted and the fixed agreement calculations of the various segmental levels (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

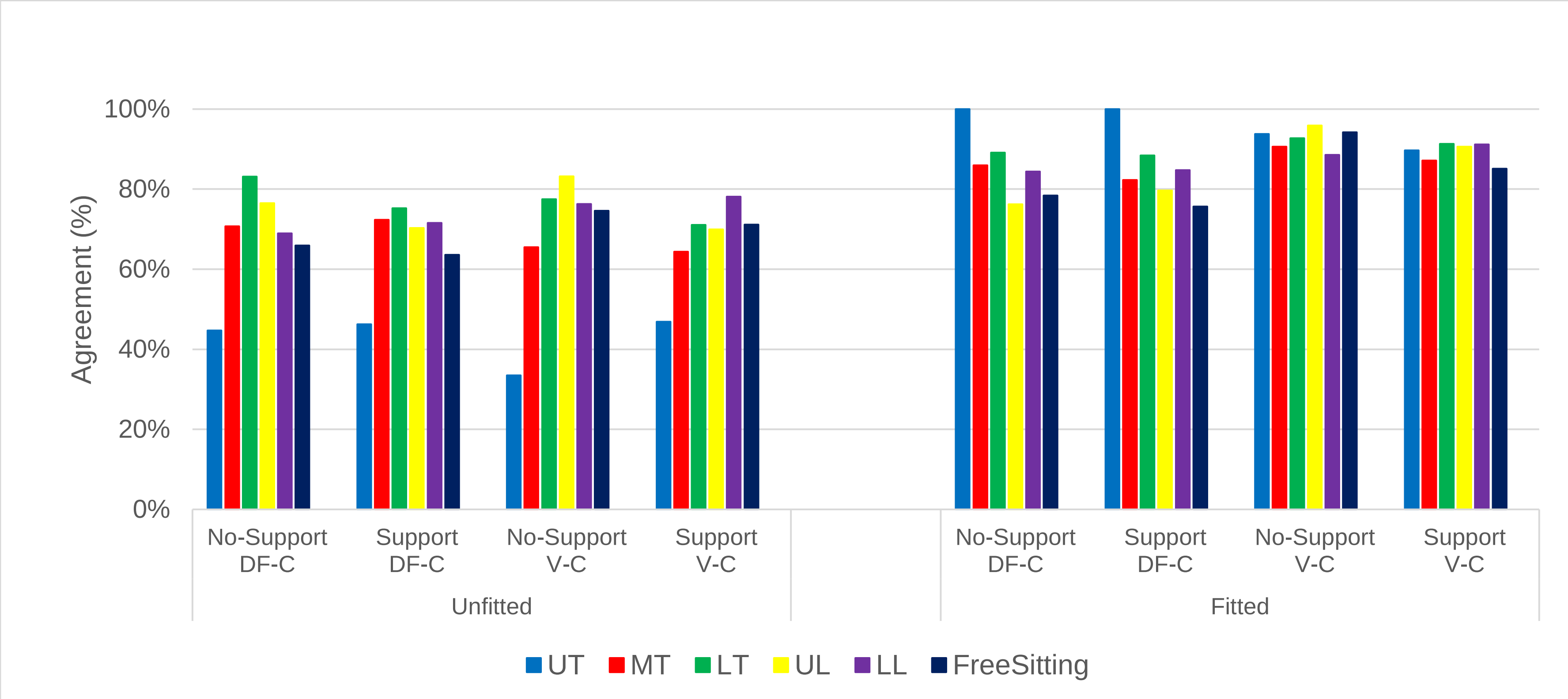
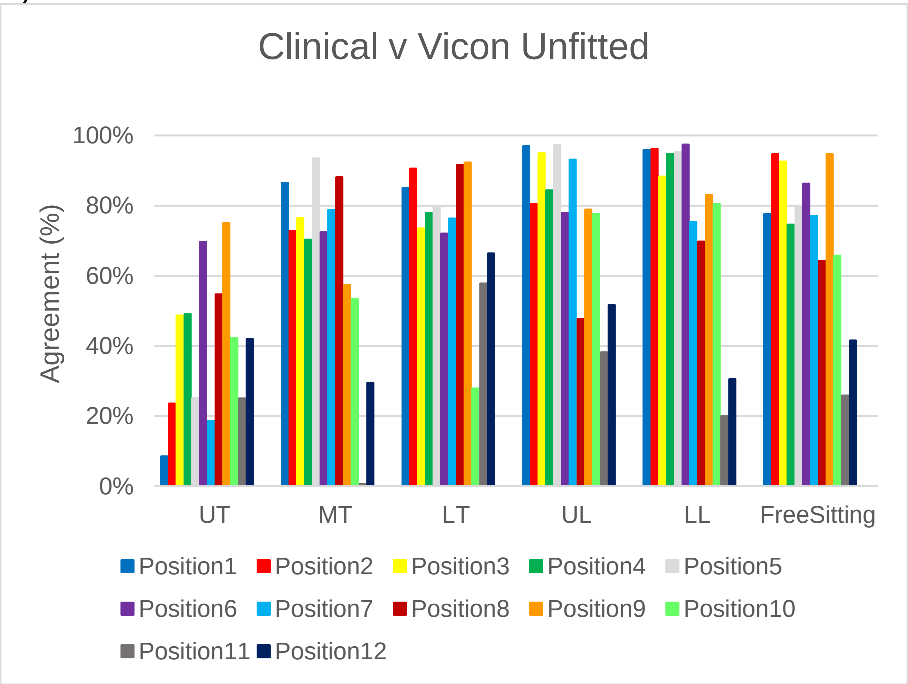


Figure X-5 Calculated agreement for No-Support and Support arms positions both for clinical v Dartfish and clinical v Vicon. Adult-group.

Showing the mean percentage agreement for the unfitted and the fitted methods of the clinical v Dartfish (DF-C) and clinical v Vicon (V-C), for the grouped No-Support and Support arm positions, for the different segmental levels: (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

A)



B)

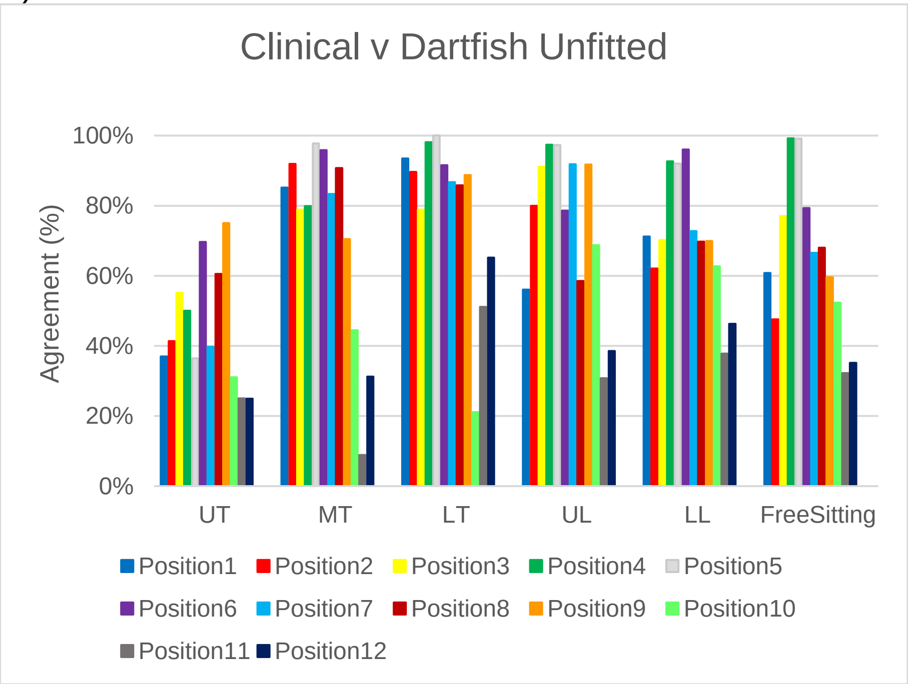
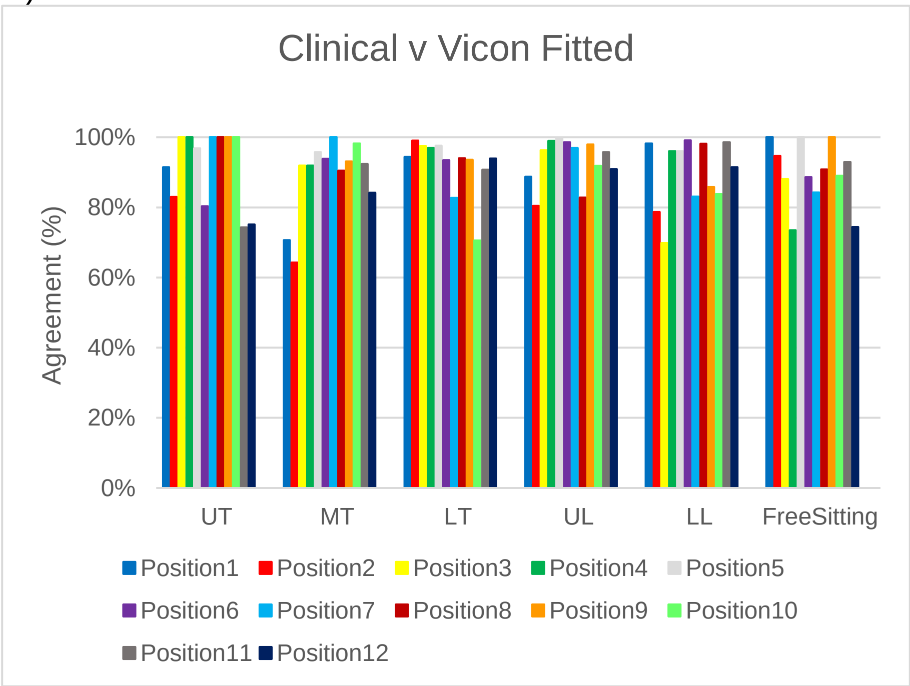


Figure X-6 Calculated agreement for the different arm positions Adult-group.

Showing the mean percentage agreement for the unfitted (A, B) and the fitted (C, D) methods of the clinical v Vicon (A, C) and clinical v Dartfish (B, D), for the different arm positions, for the different segmental levels: (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

C)



D)

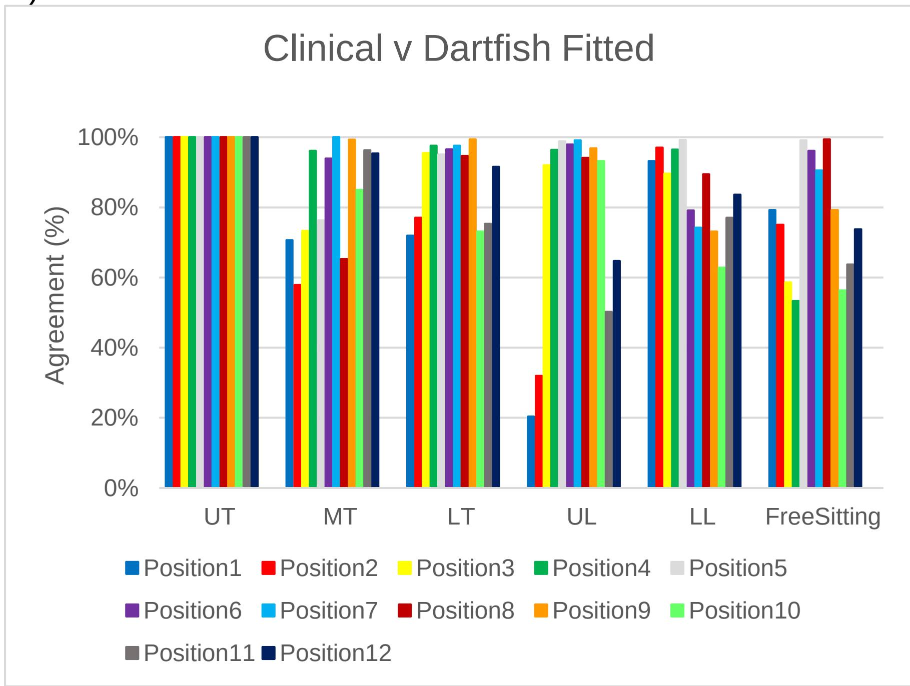


Figure X-6 Calculated agreement for the different arm positions Adult-group. (continuation).

Showing the mean percentage agreement for the unfitted (A, B) and the fitted (C, D) methods of the clinical v Vicon (A, C) and clinical v Dartfish (B, D), for the different arm positions, for the different segmental levels: (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

4. Discussion

Knowledge of both head-trunk alignment and the position of the upper limbs is required in order to understand the potential of a 3D motion capture system and of a 2D-video-based method to replicate the clinical judgement in the classification of a Controlled Kinetic Chain (CKC). A method for quantifying postural alignment in sitting has been described elsewhere in this work (Chapter IX); the present study investigated the methods required to translate the clinical classification of the upper limb component of a CKC into an objective method suitable for application in a physiotherapy practice, for example with children who have CP. The findings of the present study could provide the first steps in the development of a fully automated objective system for the evaluation of head and trunk control in sitting to complement the current clinical assessments, e.g. the Segmental Assessment of Trunk Control (SATCo).

An objective automated system should incorporate the subjective rules that are already embodied within the existing clinical practice. It should also be ‘clinically-friendly’ and not disrupt the normal practice routine, it should be ‘child-friendly’ (i.e. preferably without adhesive markers) and able to collect clean data within a crowded (visual) environment. Finally, an objective system should be simple for clinicians to use. This study has taken the first steps towards a clinically-friendly objective automated measure, based on the SATCo, by: i) making explicit and then testing a precise formulation of the clinical rules; and ii) exploring whether a reduced, minimum set of rules could objectively replicate the clinical classification.

Reliability results showed that the clinician intra- and inter-assessor reliability was excellent with either a frontal view (Adult-group) or an oblique view (Child-group). This demonstrates that assessors can extract 3D information from a single camera view but extracting this full 3D information automatically will be technically challenging. Thus, the next steps taken in this study were to determine the minimum information that might be required by an automated system based on the present information from a 3D motion capture system and a 2D-video analysis.

Results for the unfitted method showed that it was possible to classify Open-CKC (No-Support) v Closed-CKC (Support) using only the positions of the participant's hands and elbows in relation to the supported-body when using a 3D Motion Capture system for both groups of participants or using a frontal 2D-video camera for the Adult-group (Figure X-3). However, the relatively low percentages of agreement between clinicians and Vicon and between clinicians and Dartfish, particularly at higher segmental levels, were a clear indication that this method was not capturing sufficiently what clinicians observe from video. This was further confirmed by the arm position analysis where the lowest agreements for No-Support and Support grouped (Figure X-5) and independent positions (Figure X-6) were found for the UT segmental level.

Results for the fitted method showed that for both systems the agreement with the clinical judgement improved substantially by adding a single adjustable parameter (Figure X-3). This parameter (*t*) increased the minimum clearance distance from the supported-body incorporating the assistant's supporting hands and to ensure clearance of the participant's hands and elbows from the participant's body. The *t*-value was adjusted to maximise agreement with the clinical assessment separately for the 3D system and for the 2D-video analysis (Figure X-4). Furthermore, a larger *t*-value, particularly at higher levels of support (UT and MT), matched better with the clinical assessment. This implies that during a SATCo to test UT segmental level, the assistant's hands providing trunk support also potentially provide external mechanical support to the lower margin of the upper limbs. An Open-CKC is only demonstrated when the upper limbs are clear by a margin of error represented by values required for *t*. Optimal *t*-values were defined for each segmental level tested to maximise the agreement along the complete trial. It is possible that in this process, specific agreement differences were overlooked as is shown in Figure X-6 D positions 1 and 2 for UL segmental level for the clinical v Dartfish analysis. The position agreement values in Figure X-6 represent an average of all the participants, for the fitted this mean was determined by values that were between 0 and 58% for position 1, and between 0 and 57% for position 2 (one case had a 100% agreement). Detailed observation of the Dartfish fitted data, revealed that the participants who showed smaller agreement values for positions 1 and 2 were women; this could be a further indication that assessors (i.e. the human eye) can see more detail in the movement of the upper limbs in relation to the participant's own chest especially when the arm position is in front of the participant's own body.

For the 3D data of both the Adult-group and the Child-group, the parameter *t* was also applied without using clinical assessment; this was tested in the fixed-values method. Results showed that it was possible (more than 70% agreement), to replicate the clinical judgement using fixed values of *t* that were participant invariant and level of segmental support specific (Figure X-3). Using general values in this way implies that the method is fully automated i.e. clinical judgment is not needed to modify the *t*. However, this study used relatively small groups of participants; increasing the number of participants could help to refine the general *t*-values and increase the fixed-values reliability. Furthermore, it remains possible that this automated rule could be improved further using participant specific measurements.

The work developed in the present study used a 3D motion capture system and a 2D-video analysis to support the concept. There are, however, several difficulties with both these systems. From a 2D-video a clinician can detail the volume of the upper arm and see its relation to the assistant's supporting hands or the participant's body and can distinguish the presence of light touch that results in a Closed-CKC. A clinician can also easily identify external supporting elements from video such as a child's contact with parents' hands. In contrast, the 3D system and the 2D-video based analysis were based on a simplified model of the upper arms. Even if these models were more complex, it would still be difficult for a 3D motion capture system to identify light touch or for a 2D-video system to interpret the full picture as a person can. The above can potentially explain the lower agreement found for positions 11 and 12 (Figure X-6 A, B). Furthermore, external objects can only be recognised by a 3D system if they have reflective markers.

Although the position of the hands and arms in relation to independent sitting has been studied before both using video analysis [118] and a 3D motion capture system [119], those analyses were related to symmetrical or asymmetrical reaching and to the qualities of reaching and manipulation. As far as could be determined from the literature, the use of the upper limbs to compensate for poor trunk control in sitting has not previously been studied.

This study has demonstrated that the upper limb component of a CKC can be identified objectively and that it matches with the clinical judgement. The shortcomings of a 3D motion capture system and 2D-video analysis have also been identified. These difficulties could potentially be overcome by the development of a system with the characteristics of video recordings, to allow markerless assessments, but with the capacity to identify the volume of the objects and people involved in the scene. Following the principles established in this study, this new system could complement clinical assessments in neurodisability such as cerebral palsy.

5. Conclusion

This study addressed the classification of Open-CKC required for the clinical assessment of trunk control status in children with cerebral palsy. Results demonstrated that, if a participant is sitting with an aligned head-trunk, a frontal or oblique camera provides sufficient information for clinicians to make a reliable, objectively supported, clinical analysis of upper limb Open-CKC in children with cerebral palsy. The automated objective method (based on 3D motion capture data – Vicon, and 2D-video recordings – Dartfish) reduced the clinical judgement to measurement of the position of the participant's hands and elbows in relation to a defined supported-body of the head-trunk. While these simplified objective measures were less robust than the clinical judgment they demonstrate the main rules required to analyse Controlled Kinetic Chain status and thus justify future investment in application of advanced image analysis techniques to enable automatic CKC classification in a clinically-friendly manner.

XI. Quantitative Classification of the Segmental Level of Control in Children with Cerebral Palsy

1. Introduction

Full active control in sitting is determined by the ability a person has to maintain an aligned position of the head and trunk without any external support other than the seat or bench. Independent unsupported sitting is a milestone of typical development, it enables bilateral hand function and thus is vital to learning and development [6]. However, children with neuromotor disability, such as cerebral palsy (CP), have reduced or absent head and trunk control that frequently results in a lack of independent sitting ability leading to functional limitations [6]. Therapeutic interventions for these children should be tailored individually to each child's needs and directed to the promotion and achievement of sitting balance. Thus, detailed assessment of the motor function of a child is essential to determine the best therapeutic intervention. Current assessments that determine the functional abilities shown by a child include the Gross Motor Function Measure (GMFM) [18], the Chailey Levels of Ability [20], Trunk Control Measurement Scale (TCMS) [25], the Sitting Assessment for Children with Neuromotor Dysfunction (SACND) [26] and the Segmental Assessment of Trunk Control (SATCo) [29]; these are all based on a subjective observation of the child's activity[51], which has the potential to confound the evaluation outcomes. Only the SATCo identifies the specific segmental level of the trunk where control is poor or not demonstrated; it considers both the alignment of the head and trunk and the use of any external support by the child such as hand support [29]. Objective quantification of trunk control and sitting ability is desirable since it is repeatable, eliminates variability between and within assessors and offers the potential for quantifying clinical changes over time. To complement a clinical assessment, an objective system should ideally incorporate the rules existing in

[51] Refer to Chapter II for more details about these assessments.

the specific clinical test. It should also be practical for clinical use and thus 'clinically-friendly' for both the child and the therapist. Basing such quantification on the SATCo offers the potential for the most detailed objective assessment.

The SATCo systematically assesses Static, Active and Reactive control[52] in sitting at six segmental levels and free sitting, identifying the highest (most cephalo) segmental level where control is no longer demonstrated[53]. This assessment enables the clinical identification of the segmental level of the trunk where control learning should commence (the targeted segment), providing the start point to plan therapy such as Targeted Training (TT). As described in Chapter III, TT simplifies this learning process by using a sequential cephalo-caudal, segment-by-segment approach[54] mimicking the process of typical development of head and trunk control during the first year of life [53, 55-57].

Previous Chapters have demonstrated that the two components of a Controlled Kinetic Chain (CKC), i.e. head and trunk alignment and no external contact of the head/trunk or of the upper limbs, can be classified accurately from a clinical assessment and quantified using video recordings or a 3D motion capture system. In the calculation of alignment and deviation from alignment (Chapter IX) the error calculated between 2D-video-based method and a 3D motion capture system was below 4° for the majority of the segments[55]. In the classification of the position of the upper limb in relation to the supported-body (Chapter X), the agreement between the clinical and the 3D motion system was between 60-89% for adults and 48-89% for children[56]. Thus, putting these two elements together would allow an objective measure of head and trunk control of a child with CP. This study[57] presents the first quantitative classification of an Open Controlled Kinetic Chain (Open-CKC) using a video-based method. The 2D-video-based method previously validated using a 3D motion capture system as presented in

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52 Static, Active and Reactive control in sitting represent the ability a person has to maintain an independent sitting posture (static), during active movement (active or anticipatory) and to restore it after a perturbation (reactive or compensatory).

53 Refer to Appendix A for a detailed description of the SATCo test.

54 The segments as defined for the SATCo and for TT therapy are: Head (comprising head and neck), (Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Full Trunk.

55 See Table IX-4 in Chapter IX for more details.

56 See Figure X-3 in Chapter X for more details.

57 This study will be referred to as 'Levels of Control Study' in the other Chapters.

Chapters IX ‘Alignment Study’ and X ‘Upper Limb Study’ of this thesis, is introduced here as a tool suitable for clinical use since it has the potential to be ‘clinically-friendly’ for both the child and the therapist. Furthermore, it opens the possibility of development of automated quantitative tools to create an outcome measure that is similar to the pre-existing assessment processes used in clinical physiotherapy practice. Analysis of the three elements of control (Static, Active and Reactive) is necessary for a complete assessment of the control status of a child with a neuromotor disability. This status is clinically identified as the “segmental level of control” and is the most cephalo segment at which control (Static, Active or Reactive) is not demonstrated [29]. This definition is the one used in the present project. This study focussed specifically on the Static element. This decision was based on i) the fact that Static control is the basis on which Active and Reactive control are acquired [54, 143] and is therefore of greatest clinical value, and ii) the need for the measure of Static control to be robust. The analysis of the Active and the Reactive trials described in Appendix B showed that further work is required in these areas to enable a robust measure to be developed.

The objectives of this study were i) to test the extent to which the quantitative classification captured the clinical assessment for the segmental level of trunk control during a SATCo; ii) to assess the extent to which clinical assessment is supported by objective correlates; and iii) to provide recommendations for development of a robust, clinically suitable system that addresses the limitations of the tool developed thus far.

2. Methods

2.1 Participants

Twelve children (9 males, 3 females, mean age 4.52 years ±2.4, mean height 0.97m ±0.1, and weight 16.15kg ±7.5 at recruitment) were included in the study. Detailed anthropometric measurements can be found in Table XI-1.

All children had a clinical diagnosis of cerebral palsy (CP). Inclusion criteria for this study were:

- children with neuromotor disability resulting in problems of postural control and
    - whose parents or guardians have demonstrated capacity to give consent, having already provided consent for the Targeted Training (TT) therapy and
    - who were on their first course of TT

Exclusion criteria were:

- fixed bony deformity or other structural problem of the spinal joints
- uncontrolled epilepsy (more than one fit a day)
- other serious systemic illness
- severe athetosis
- both parents or guardians did not have an understanding of English language either written or spoken.

Children's parents provided written informed consent on behalf of their child with child assent where possible.

The children were seen at The Movement Centre, Oswestry, during their regular Targeted Training review sessions. Children wore only their underwear/nappy or shorts as usual for their clinical assessments. This allowed more accurate palpation of anatomical landmarks for marker placement.

Table XI-1 Participants' anthropometric characteristics.

Participant	Sex	Initial Age (years, months)	Initial Height (m)	Initial Weight (kg)
LS01	Male	10y 11m	1.27	37.7
LS02	Female	1y 11m	0.81	12.2
LS03	Male	4y 05m	1.04	16.5
LS04	Male	5y 1m	0.90	12.9
LS05	Female	1y 9m	0.77	10.1
LS06	Male	5y 4m	0.99	14.7
LS07	Male	3y 11m	0.96	13.9
LS08	Female	6y 1m	1.12	23.4
LS09	Male	3y 3m	0.88	9.0
LS10	Male	4y 5m	0.94	12.4
LS11	Male	5y 6m	1.04	18.9
LS12	Male	1y 10m	0.96	12.04
MEAN		**4.52**	**0.97**	**16.15**
SD		**2.42**	**0.13**	**7.51**

2.2 Procedures

A full SATCo test was done as part of the routine Targeted Training review starting with testing of Head control and continuing down until Free Sitting, or as low as the child's segmental trunk control allowed. The same Physiotherapy Assistant provided the manual support to the trunk for all the sessions. When needed, extra manual support was provided by a second clinician to ensure an aligned posture below the level of support; this was done following the guidelines for the SATCo assessment [29].

Markers were placed on specific landmarks of the head, trunk and pelvis, following the model previously developed (Figure XI-1).

Video was recorded without interruption from the moment all the markers were in place and the SATCo about to commence until the researcher was satisfied that the SATCo data collection for this project was completed for that child. A 'Done!' signal was given by the person directing the data collection session[58] and video recording was stopped.

Markers were then removed and the normal clinical assessment continued.

Data was collected for as many sessions as possible while the child was still participating in his/her first course of TT therapy[59]. The numbers of weeks between one assessment and the following was determined by clinical needs.

[58] In all but one session this person was the PhD student. The PhD student was unable to attend one of the sessions and it could not be rescheduled. It was decided that the physiotherapist assigned to the child was the person that would direct the data collection process. This physiotherapist was familiarised with the process and a 'Data Collection Steps' document had been provided in advance, with plenty of time to give clarifications if needed. There was no noticeable variation in the data resulting from this session to any others for that child.

[59] A course of Targeted Training therapy is typically planned to last 9 months; the nine-month period commences at the appointment in which the child is supplied with the (personalised) stander. Review appointments are planned to take place every eight weeks, which represents a maximum of 5 contact points in one course of therapy.

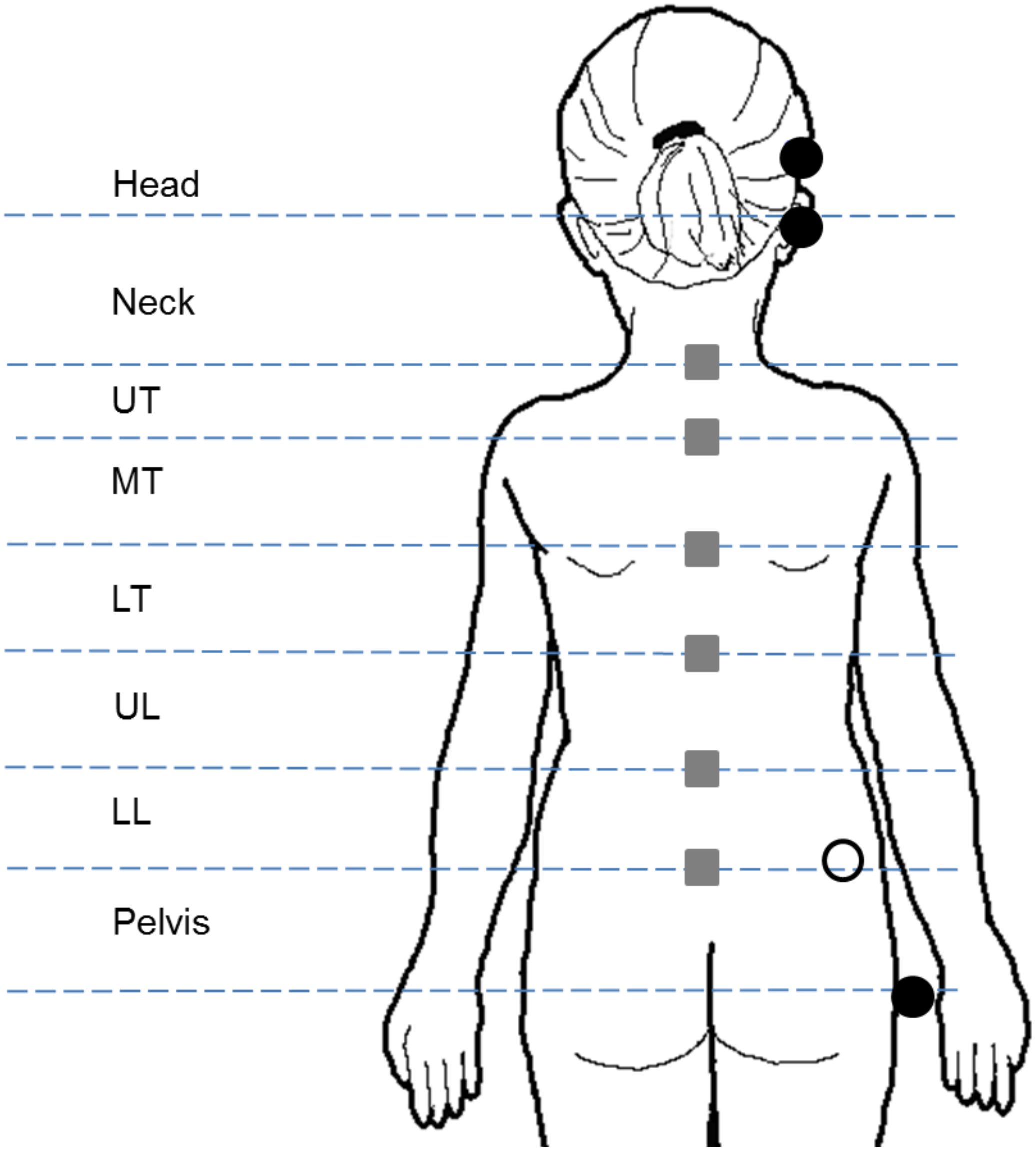

Figure XI-1 Marker location and limits of the trunk segments.

Squares show markers placed on the back of the participant: spinous process of the seventh cervical vertebra (C7), third, seventh and eleventh thoracic vertebrae (T3, T7 and T11), third lumbar vertebra (L3) and first sacral vertebra (S1). Dots show markers located on the side (black circles) or front of the child (white circle): right ear tragus, right temporal fossa (in a vertical line from the ear tragus when the head was in neutral position), greater trochanter and right anterior superior iliac spine (ASIS).

2.3 Apparatus and Measurements

Video was recorded at 25Hz from a video camera (JVC, HD Everio RX110) mounted on a levelled tripod on the right side of the child at a constant distance of 3.0m and a constant height of 0.70m. This view allowed recording of sagittal plane movements of the head and trunk. Small coloured blocks (2x2x2cm) were used to improve the lateral visualization and tracking of the back landmarks (Figure XI-2).

Coordinates of landmarks from video were obtained using the Dartfish marker tracking tool (Dartfish 7, TeamPro 7.0)[60]. The same operator processed all videos[61]. Following the methods described in Chapter VIII, trunk segments were created and segmental angles were estimated for the alignment component of trunk control.

A second camera was placed at right diagonal front (approximately 45°) to allow the parent to stand in front of the child without obstructing the camera view. The camera was at a constant distance of 2.5m and a constant height of 0.75m. The oblique view recordings were used to confirm the position of the arms for the upper limb component of trunk control.

[60] For a detailed description of this process, refer to Methods (Chapter VIII).
[61] Dartfish operator consistency was assessed as part of the ‘ Alignment Study’ (Chapter IX, Section 3.4.2 and 4.2).

Figure XI-2 Side view of a participant.

Side view of a child, showing how the Small coloured blocks improved visualisation.

2.4 Data Processing and Analysis

Only the Static element of the SATCo of each level tested was included for analysis. The Static test of each segmental level tested, is referred to in this chapter as a 'trial'. For each clip, the video recordings from the two cameras were manually synchronised through the identification of a common key position in Dartfish[62]. From the synchronised clips, the selection of Static trials was refined using the information of the upper limb position. This refinement was done by one assessor who selected the clip section where the child's upper limbs were clear of external support, or were as free of contact as the child's control allowed. This selection was done following the methods established in Chapter X 'Upper Limb Study'.

The segmental level of control of each session was defined from both a clinical assessment and from a video-based measured analysis.

To facilitate the clinical assessment of the segmental level of trunk control, all the Static recordings of a session were organised in a continuous video with the header of the trial level before each trial.

2.4.1 Model of Alignment

An additional video clip (alignment-clip) was created from the videos of the sagittal view to generate a model of alignment for each child for each session.

The definition of postural alignment in sitting had been consolidated in a focus group consisting of four physiotherapists, each with 5 to 20 years of experience performing SATCo and using their standard working practice definition[63]. The model of alignment was constructed based on this agreed definition.

The model of alignment per child was created following the methods developed for Chapter IX and described in detailed in the 'Methods' Chapter (Section 4.2.1):

i) Five assessors identified the 2D-video frames where the child's posture was aligned.

[62] See Methods (Chapter VIII) for a detailed description of how this process was done.
[63] See 'Alignment Study' (Chapter IX) for a detailed description of how this process was done.

ii) The segmental angles (created from 2D-video coordinates exported from Dartfish) of those frames were then used to calculate the aligned posture based on the information of each separate assessor.

iii) For each session, the participant's model of alignment was created, as the mean (± standard deviation) of the aligned segmental angles of each assessor's model.

2.4.2 *Trial Length Reduction to 5 Seconds*

For the measured analysis, each trial was reduced to a length of only 5 seconds, this being the time criterion for confirmation of the presence of Static control in the SATCo. The steps below were followed to find the 5 seconds where the child was showing the best control, i.e. least cumulative deviation from alignment (Figure XI-3):

i) Calculation of absolute segmental angles (A_{sa}) from the segmental angles (A_s) and the aligned angles (A_a) (Figure XI-3, A):

$$A_{sa} = A_s - A_a$$

ii) Calculation of segment misalignment (MA_s) for each unsupported segment (Figure XI-3, B):

$$MA_s = (A_{sa})^2$$

iii) The cumulative misalignment (CMA) was calculated for a duration of 5 seconds, for a constant (k):

$$CMA(k) = \sum_{t=0}^{k+5} (MA_s)_{S=1}^{n}$$

iv) Where k was defined to refer to each possible start, i.e. each time point for which the trial could be 5 seconds long (Figure XI-3, C, D).

v) The start point for the trial was defined as the start point where the cumulative misalignment was smaller:

$$Start = t, minCMA$$

vi) The end point for the trial was defined at 5 seconds after the start point:

$$End = Start + 5_{sec}$$

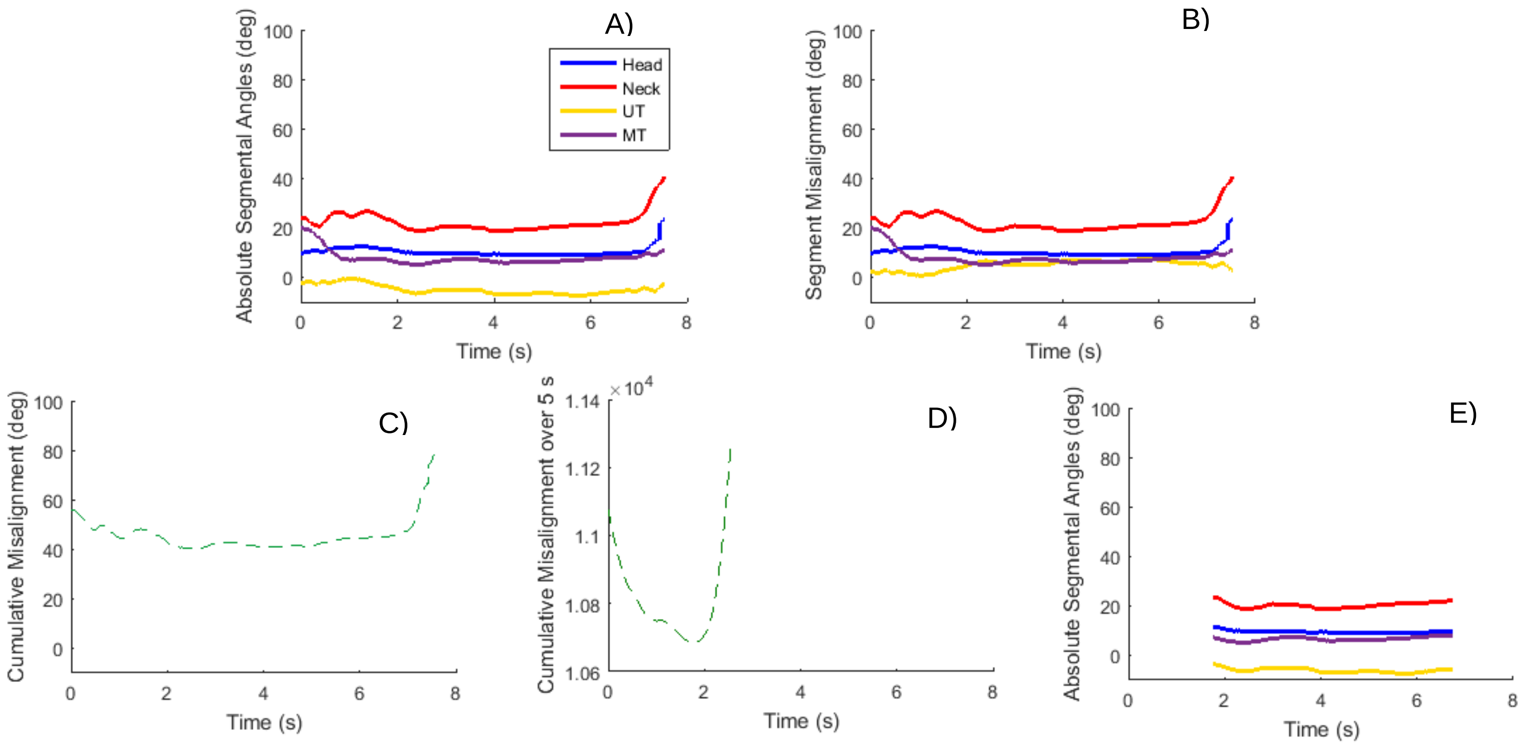

Figure XI-3 Representative example of a trial length normalisation to 5 seconds.

Showing for a Mid Thoracic (MT) Static trial A) absolute segmental angle traces for the unsupported segments; B) the calculated segment misalignment for each unsupported segment; C) the cumulative misalignment; D) the cumulative misalignment for each possible start; and E) the absolute segmental angle traces for the 5 seconds where the cumulative misalignment was smallest.

2.4.3 *Clinical Evaluation of Control: Definition of Concept and Processing*

Clinically, Static control is credited at a given trunk segment when the child can maintain a neutral trunk posture for a minimum of 5 seconds with the arms and hands in the air [29]. This rule can be divided into the following parameters:

i) The child maintains a neutral vertical trunk posture in the sagittal and frontal planes.

ii) Stable neutral vertical alignment allows a brief deviation no more than a threshold of 20°.

iii) Alignment allows for normal cervical, thoracic and lumbar curves appropriate for age (Table XI-2).

iv) If the child’s attention is briefly lost, accompanied by a head turn, but a vertical position is maintained, is still valid as alignment.

v) The child maintains the head-trunk-arms kinetic chain with no support from external objects.

vi) The above lasts for the 5 seconds that constitutes a Static trial.

Four assessors completed the assessment of the segmental level of control from the videos. Two assessors evaluated all the videos, the other two assessors rated the videos of the children for whom they were not the clinically responsible physiotherapist. This generated three evaluation judgements per session. For comparison with the objective outcome, the clinical judgement value was calculated as the median of the segmental level of control identified by the separate assessors (mC).

The videos of the different sessions were presented in a random order to the assessors.

Table XI-2 Aligned static sitting posture.

Qualitative description of the aligned static sitting posture agreed in the focus group.

	Description
Head and neck	Chin: Neither protracted nor retracted
	Eyes: Looking forward
	Ear (tragus): Aligned with the hip
Shoulder	Shoulder girdle: Neither protracted nor retracted
Trunk	Smooth and continuous spinal curvatures Thoracic spine: Near flat as possible Lumbar spine: Slight lordosis or flat
Pelvis	Neutral
Lower limbs	Hip – Knee angles: 90º - 90º

2.4.4 Objective Measure of Control

The objective measure of the segmental level of Static control used the segmental angles calculated from the 2D-videos for each session to reflect the clinical assessment of control. The rule defined for the objective measure of control was: measured control was rated positive for a trial when the position of all the unsupported segments was below an established threshold value for 5 seconds. This defined the lowest segmental level tested where all the unsupported segments were classified as ‘controlled’. To match the clinical concept, the level of control was then defined as the segment immediately below the ‘measured controlled’ segmental level.

The steps that enabled the implementation of this rule were:

i) Definition of the variables used:

The following variables were calculated for the unsupported segments of each trial:

- Mean Angle (M): calculated as the mean of the Absolute Segmental Angles.
- Standard Deviation (SD): calculated as the standard deviation of the Absolute Segmental Angles.
- Absolute Mean Deviation plus SD (M+SD): calculated as the addition of the absolute value of the Mean Angle of a segment and the standard deviation for that segment.
- Maximum Absolute Angle Deviation (Max): identified by the absolute maximum value of the absolute Mean Angle. It represented the farthest position from the aligned posture reached by a segment during a trial.

ii) Definition of thresholds:

The threshold served for a classification of the measured control. The threshold values used in the analysis presented in the results section of this Chapter were defined with a systematic test of threshold values. Threshold values range from 1° to 40° by 1° increments.

iii) Measurement of control for the separated variables:

Static control for each session was defined following these steps:

- For each unsupported segment of each segmental level tested, the variable was calculated.
- If at any time any unsupported segment had a value for the variable larger than the defined threshold, the segment was classified as no-control.
- If all the unsupported segments were in control, then the child was showing control for that segmental level tested.
- The 'controlled' segmental level was defined as the lowest segment (most caudal) tested where the child demonstrated control.
- The measured segmental level of control for a session was then identified from the 'controlled segment' +1.

iv) Calculation of the agreement between the measure and the clinical assessment of the segmental level of control:

The agreement was calculated as the error of the difference between the clinical and the measured segmental level of control for each session.

For each variable and threshold, the mean error (ME) and root mean squared error (RMSE) of all the sessions were calculated (Figure XI-4 and Figure XI-5).

3. Results

Twelve children were recruited for this study. Only one child withdrew from the study after the first session (the reason given by the child's mother was distress of the child and family). A total of 39 sessions were recorded. Of these only 28 were included in the analysis (Table XI-3); the data from each session was processed as an independent measure. The 11 that were excluded did not meet the selection criterion for objective analysis.

The average (±SD) number of sessions recorded per child was 3 (±1.1) distributed as follows: two children took part in 2 sessions, five in 3 sessions, one child in 4 sessions and three children in 5 sessions (Table XI-3). The minimum and maximum intervals between sessions were 7 and 17 weeks respectively.

3.1 Model of Alignment

To test the extent to which the quantitative classification captured the clinical assessment for the segmental level of trunk control during a SATCo, the two components of control (alignment of the head and trunk, and unsupported segments above the segmental level tested) had to be identified. A quantitative model of alignment was created as the reference to calculated segmental deviation from alignment. The aligned posture for each child and each session was quantified from the video-based marker coordinates exported from Dartfish (Table XI-4).

Sessions in which an aligned model was created from a clip that was not the lowest level tested, had missing segments due to visual obstruction of the markers. Aligned segmental angles were calculated only for the segments between two consecutive markers that were present in the complete alignment-clip. This generated models where there were no aligned segmental angles.

For the Static trials, the movement of the segments with no aligned segmental angle was excluded from analysis.

Table XI-3 Number of sessions recorded per child.

Participant	# Sessions Recorded	# Sessions included for Analysis
LS01	3	2
LS02	3	1
LS03	2	2
LS04	4	4
LS05	5	2
LS06	3	2
LS08	5	5
LS09	3	1
LS10	3	2
LS11	2	2
LS12	5	5
MEAN	**3**	
SD	**1**	

Table XI-4 Aligned posture per participant per session.

Showing the value of the aligned mean angle in degrees (°) of each segment per session from the video based system. N/A is used where there were no segmental angles available. Also showing the Mean angle and standard deviation (SD) of the complete group.

Participant	Head	Neck	UT	MT	LT	UL	LL	Pelvis
LS01	-4.47°	32.03°	36.95°	12.29°	1.31°	1.96°	6.17°	24.47°
LS01	-9.33°	36.81°	14.47°	2.50°	-7.78°	3.06°	N/A	19.20°
LS02	24.88°	45.28°	17.95°	8.04°	3.69°	N/A	N/A	29.30°
LS03	-5.09°	38.32°	21.97°	8.88°	0.33°	5.48°	7.78°	27.04°
LS03	-6.75°	33.81°	25.20°	11.16°	2.94°	0.43°	0.41°	30.80°
LS04	-1.56°	49.26°	20.39°	N/A	N/A	N/A	N/A	N/A
LS04	-2.46°	39.01°	25.97°	N/A	N/A	N/A	N/A	N/A
LS04	-6.94°	54.10°	26.06°	N/A	N/A	N/A	N/A	N/A
LS04	4.73°	54.67°	9.15°	N/A	N/A	N/A	N/A	N/A
LS05	-6.37°	35.12°	25.06°	1.94°	-0.01°	N/A	N/A	24.18°
LS05	1.53°	49.17°	20.48°	3.65°	-6.58°	-2.95°	1.93°	17.15°
LS06	4.54°	46.73°	29.99°	7.97°	N/A	N/A	N/A	N/A
LS06	-8.23°	50.71°	20.44°	N/A	N/A	N/A	N/A	N/A

Table XI-4 Aligned posture per participant per session (continuation).

Participant	Head	Neck	UT	MT	LT	UL	LL	Pelvis
LS08	4.94°	46.70°	28.67°	6.42°	-5.01°	-1.94°	14.52°	9.51°
LS08	-5.12°	45.86°	31.49°	4.56°	-4.90°	0.07°	9.71°	17.36°
LS08	2.26°	46.30°	28.76°	4.34°	-2.48°	1.11°	15.57°	14.94°
LS08	-6.69°	50.91°	26.16°	9.11°	-3.85°	1.42°	9.74°	17.45°
LS08	5.24°	38.87°	29.02°	0.04°	-5.23°	-5.20°	6.57°	33.04°
LS09	5.80°	42.50°	26.01°	4.44°	2.93°	N/A	N/A	N/A
LS10	-0.04°	53.96°	7.66°	1.22°	6.88°	-0.88°	4.31°	24.99°
LS10	-1.71°	46.23°	20.22°	9.20°	1.28°	2.46°	N/A	20.98°
LS11	-1.90°	38.76°	11.90°	1.78°	4.17°	N/A	N/A	27.11°
LS11	3.88°	41.66°	21.70°	19.01°	-2.53°	N/A	N/A	12.23°
LS12	-9.75°	32.47°	16.56°	2.40°	6.54°	-0.50°	-0.70°	36.55°
LS12	3.10°	53.39°	22.51°	12.23°	N/A	N/A	10.07°	28.30
LS12	-3.36°	25.02°	17.98°	10.65°	-3.47°	-2.93°	N/A	26.21°
LS12	2.74°	29.63°	16.67°	6.36°	5.08°	6.19°	N/A	N/A
LS12	-2.08°	34.00°	32.80°	0.67°	N/A	N/A	N/A	24.01°
Mean	**-0.65°**	**42.55°**	**22.58°**	**6.47°**	**-0.33°**	**0.52°**	**7.17°**	**23.24°**
SD	**6.96°**	**8.20°**	**7.05°**	**4.70°**	**4.50°**	**3.12°**	**5.14°**	**7.04°**

3.2 Identification of the 'Control Threshold'

The ME and RMSE calculated between the different variables (M, SD, Max, and M+SD) and the median of the assessors (mC) assessment, for threshold values 1-40°, are presented in Figure XI-4 and Figure XI-5 respectively.

The threshold values where errors were smallest (control threshold) were selected to further represent the difference between the clinical and the measured assessment of control.

3.3 Comparison of the Clinical and The Measured.

The control threshold selected for each variable for the detailed comparison between the clinical and the measured level of control were:

- Mean Angle (M) threshold = 6°
- Standard Deviation (SD) threshold = 4°
- Absolute Mean Deviation plus SD (M+SD) threshold = 14°
- Maximum Absolute Angle Deviation (Max) threshold = 17°

Figure XI-6 shows the comparison of the clinical and the measured level of control for all the sessions assessed using the above defined control threshold values.

For these variables, the ME was 0.143 for M6, 0.036 for SD4, 0.214 for M+SD14, and -0.107 for Max17. The RMSE calculated was 2.405 for M6, 2.212 for SD4, 1.753 for M+SD14, and 1.763 for Max17.

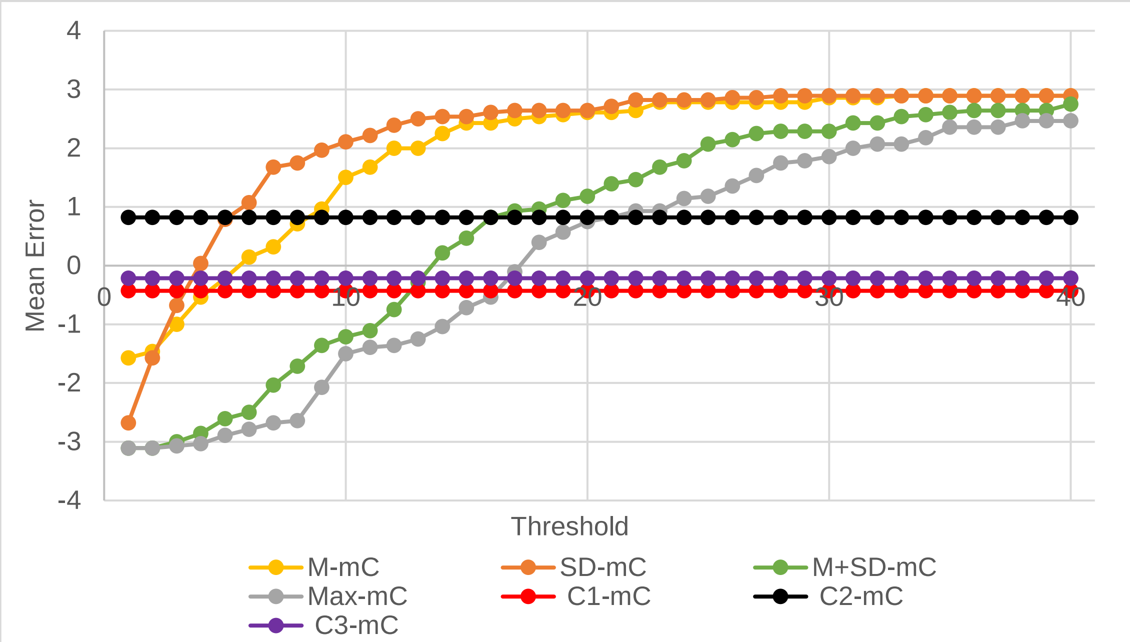

Figure XI-4 Calculated mean error (ME) for threshold values 1-40°.

Showing for each threshold value 1-40° the mean error (ME) between, Mean Angle (M, yellow), Standard Deviation (SD, orange), Absolute Mean Deviation plus SD (M+SD, green), Maximum Absolute Angle Deviation (Max, grey), and the median of the assessors (mC). The ME between assessors (C1 red, C2 black, C3 purple) and the mC is included as reference.

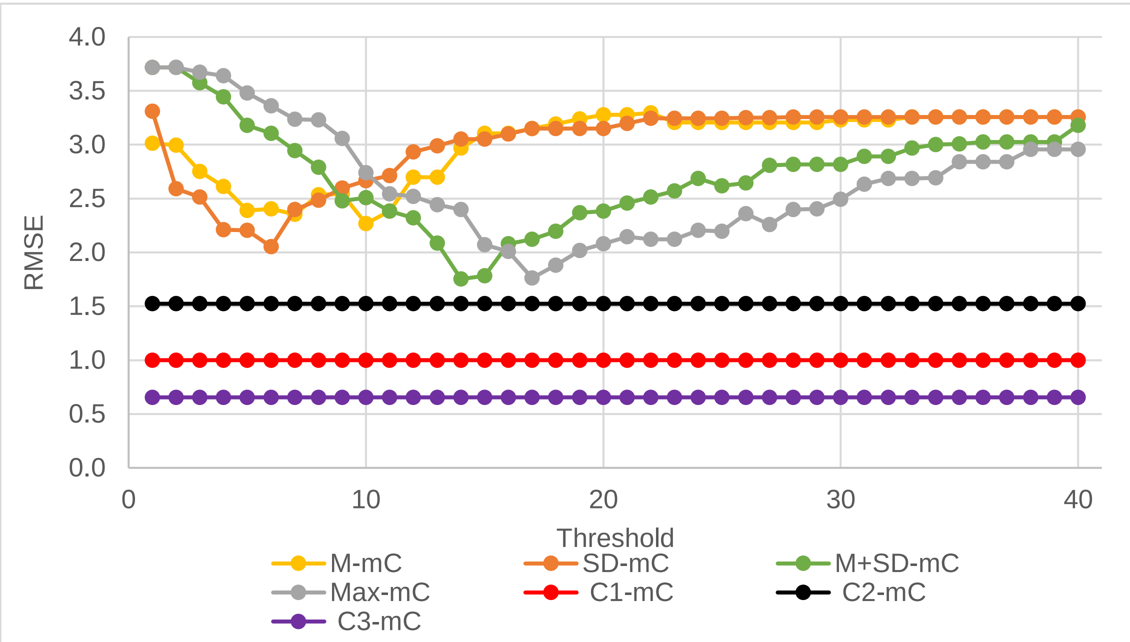

Figure XI-5 Calculated Root Mean Square Error (RMSE) for threshold values 1-40°.

Showing for each threshold value 1-40° the Root Mean Square Error (RMSE) between Mean Angle (M, yellow), Standard Deviation (SD, orange), Absolute Mean Deviation plus SD (M+SD, green), Maximum Absolute Angle Deviation (Max, grey), and the median of the assessors (mC). The RMSE between assessors (C1 red, C2 black, C3 purple) and the mC is included as reference.

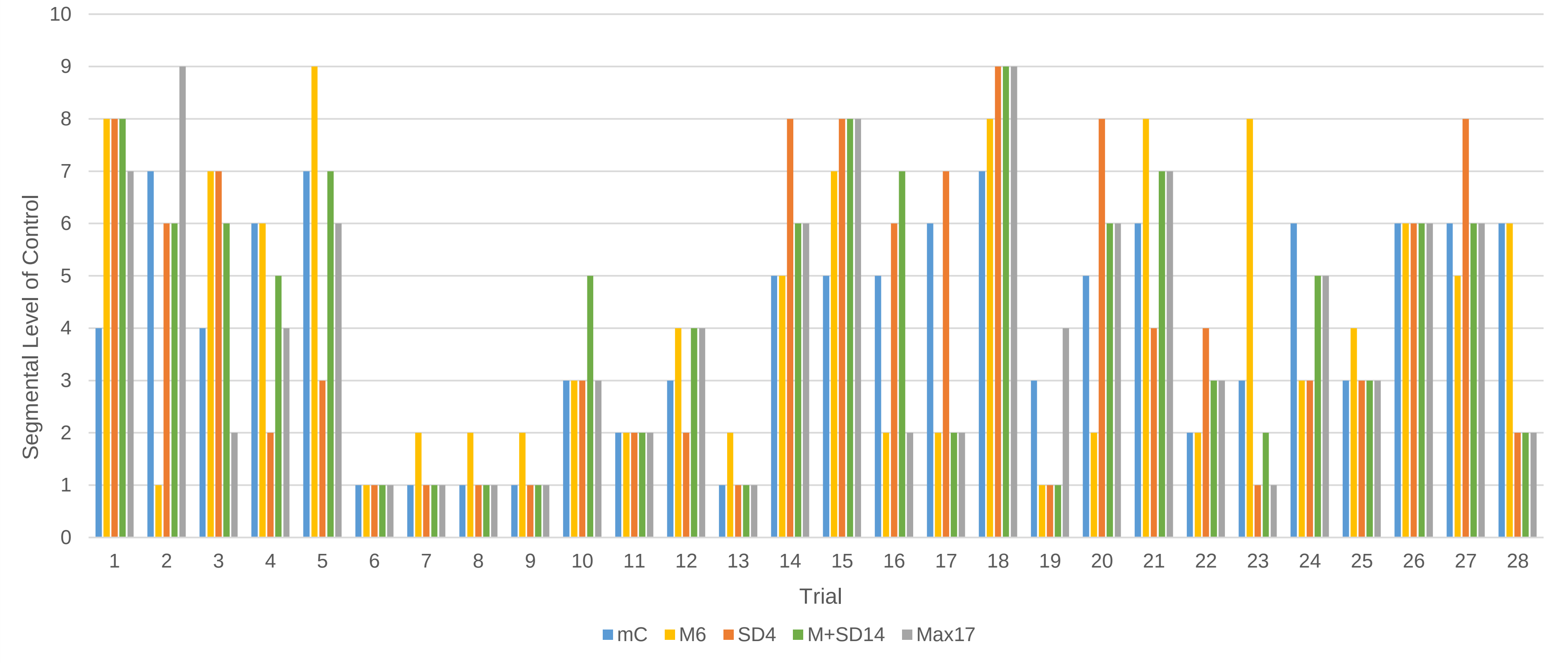

Figure XI-6 Clinical vs measured assessment of the level of control not demonstrated.

Showing in blue the median value of the level of control for the assessors (mC) against the measured level of control when using the Mean Angle (M_6, yellow), the Standard Deviation (SD_4, orange), the Mean Absolute Deviation plus Standard Deviation ($M+SD_{14}$, green), and the Absolute Maximum Deviation (Max_{17}, grey). The independent sessions relate to the participants as follows: LS01 = 1,2; LS02 = 3; LS03 = 4, 5; LS04 = 6-9; LS05 = 10, 11; LS06 = 12, 13; LS08 = 14-18; LS09 = 19; LS10 = 20, 21; LS11 = 22, 23; LS12 = 24-28.

4. Discussion

Quantitative assessments serve as an objective complement for clinical evaluations in, for example, a physiotherapy practice. The quantitative analysis eliminates the subjective component that can confound the outcomes of a test. A quantitative assessment offers the possibility of creating an objective reference for both a universal database for a specific condition and to form the base line for a person and his/her progression in relation to a specific condition or therapeutic intervention. As a complement to a clinical evaluation, an objective assessment tool should incorporate the rules existing in the clinical tests, as well as be practical and clinically-friendly both for the patient and for the therapist.

The quantitative classification of the segmental level of control presented in this study was developed from the principles of the Segmental Assessment of Trunk Control (SATCo). SATCo identifies the highest trunk segmental level where a child with a neuromotor disability is no longer demonstrating full active control in sitting; i.e. the segmental level where the child can no longer maintain an aligned position of the head and trunk with his/her head, trunk or upper limbs free of any external support (no demonstration of an Open Controlled Kinetic Chain, Open-CKC). In this study, the most practical method of obtaining this information quantitatively was to identify the lowest trunk segmental level where the child was demonstrating an Open-CKC and adding a value of one segment to the result, i.e. defining the segmental level of control as the segmental level immediately below the lowest segment where Static control was demonstrated. The methods used for the identification of both components of an Open-CKC rely on a 2D-video-based method and are equivalent to the clinical SATCo assessment. As described above, the child’s use of external support was identified from the oblique view video recordings, following the methods described in Chapter X. This was used to select trials for assessment of the alignment component. The position and displacement of the head and trunk segments in relation to an aligned position, was quantified from the lateral view video recordings; these enabled tracking of markers (in Dartfish) and segment angles reconstruction (in MATLAB) as described in Chapter VIII ‘Methods’ and Chapter IX ‘Alignment Study.

Although the SATCo evaluates Static, Active and Reactive elements of control for a complete assessment of the segmental level of control of a child with a neuromotor disability, this study presents only the development of a quantitative measuring method for Static control. Static control is the basis on which Active and Reactive control are acquired; the development of a robust method for the quantification of Static control, as established in this first approach, is therefore of paramount clinical value. A group of twelve children who were participating in their first course of Targeted Training (TT) was included for the development and testing of this method. Between two to five sessions were presented for each child. Difficulties in the assessment of children with CP are well recognised; in many cases potential errors in the data collection were identified within the session and corrected; other data collection difficulties were only recognised during the video processing stage. Markers that were either partially or totally missing due to visual obstruction was one such factor and is one of the limitations of using 2D-videos for movement analysis. In a few cases, marker obstructions generated alignment models with missing aligned segmental angles. Nevertheless, the mean aligned segmental angles of all the sessions included in the analysis (Table XI-4) showed mean± SD values that were similar to the mean aligned angles presented in Figure IX-6 above, for the group of adults. This further supports the assessor reliability in the identification of aligned posture in sitting.

The definition of the measured segmental level of control followed the clinical evaluation parameters for the identification of Static control. Each trial was reduced to a duration of 5 seconds according to the SATCo. The SATCo parameter of “stable neutral vertical alignment allows a brief deviation no more than 20°” (pg.256) [29] was used to identify the threshold at which each variable had the best match with this concept. This parameter was also defined as the main rule for the quantified measure of control. In the present method development, it was not technically possible to replicate the clinical parameter “if the child’s attention is briefly lost, accompanied by a head turn, but a vertical position is maintained, is still valid as alignment”. This parameter could be included in a future development through the refinement of the objective rules and the development of tools with the capacity to analyse movement in a 3D space. The measured segmental level of Static control in this study was then calculated using different variables (Mean Angle, M; Standard Deviation, SD; Absolute Mean Deviation plus SD, M+SD; and Maximum Absolute Angle Deviation, Max) and the individual outcomes then compared to the collective clinical judgement. At a 20° threshold, the Mean Error (ME) for each variable showed that the segmental level of control measured was overestimating control against clinical judgment between 1 and 3 segmental levels (Figure XI-4). RMSE results for each of the variables showed that the best agreement was found for M and SD was 6° and 4° respectively, for the M+SD was 14° and for Max 17° (Figure XI-5). At these controlled thresholds, the general measured segmental level of control for the M+SD and the Max had a better agreement with the mC, than the M and the SD. This can be explained by understanding that the M+SD and the Max are variables that reflect better the "brief deviation no more than 20°" parameter, as both variables incorporate a range of movement from alignment.

Although there are differences between the measured and the clinical segmental level of control, this study presents a first approach in the quantification of the level of control using a 2D-video-based method. A 2D-video-based quantitative method can be used for the quantification of both components of control during the assessment of motor control in sitting for children with CP. This has allowed an objective measure of the segmental level of trunk control. 2D-video analysis, however, has limitations; one limitation relates to the obstruction of markers that can result in missing segmental information which, in turn, might restrict the quantitative analysis. A partial quantitative analysis may be one of the causes for some of the differences found in the identification of the segmental level of control between the measured method and the median of the assessors. The obstruction of markers limitation could be overcome with the development of a markerless system, based on the present analysis.

The methods and results presented in this study provide the basis for recommendations for the development of a robust, clinically suitable system for the automated objective assessment of motor control. This Chapter has clearly shown how the quantitative classification can capture the general clinical parameters used in the identification of the segmental level of trunk control during a SATCo. The objective rule implemented in this study is most likely a subset of the rules used subjectively by the assessors; the overestimation of segmental level of control means that the quantitative method is partially capturing the clinical judgement, and it would be expected a closer match between objective and clinical assessment when the other elements are included in the analysis. Additionally, to fully reflect the clinical assessment it would be necessary to include the Active and Reactive tests at each segmental level. The combined information from these elements provides a complete picture of the control status of a child. Furthermore, Active and Reactive information provide complementary information to the Static element as done in a clinical context where assessors can grant Static control at a given segmental level tested if Active or Reactive control are demonstrated at that same segmental level. This is based on the principle that Static control is the fundamental basis on which Active and Reactive control are acquired [54, 143]. As presented in Chapter IX, use of a single video camera can result in limitations in the objective quantification of head and trunk movements; these limitations arise from the obstruction of markers and/or by the participant's movement in a plane of motion different than the plane that has been recorded. This is further explained in Appendix B, where it was shown how the objective evaluation of the Active and Reactive control might be compromised when using a single camera. In order to fully assess head and trunk control of children with a neuromotor disability, the development of an automated tool should, therefore, be markerless to avoid obstructions and to make it more child-friendly. The automated tool should also consider movement in a 3D space, this information could be obtained by the synchronized recording of two views of the participant (e.g. lateral and frontal), or by the use of a camera capable of obtaining 3D information from a 2D view. New objective methods developed to provide complementary information to the clinical assessment should, however, maintain a 'video-like' view principle; this would make the objective assessment clinically-friendly by not disrupting the clinical assessment, and enabling the therapists to relate to the information that is presented in a more 'traditional' manner.

5. Conclusion

The development of a quantitative measure from a well-defined systematic assessment such as SATCo, permits the initial development of quantitative tools based on ‘clinically-friendly’ methods such as 2D-video recordings. The importance of developing an objective measure is to enable the quantification of change and to support the subjective clinical findings. Objective automated assessments methods that could derive from this first development, have the potential to be modified and used to complement existing assessments for children other neuromotor disabilities, such as muscular dystrophy, or with musculoskeletal conditions such as idiopathic scoliosis. They have also the potential to be implemented for the assessment of adults in many settings where physiotherapeutic assessment is fundamental including clinical therapeutic practice, sport and exercise, and occupational health.

Discussion

XII. Discussion and Future Work

Children with neuromotor disabilities, such as cerebral palsy (CP), require an appropriate and comprehensive plan to address their specific limitations. It is essential to develop assessment tools that can objectively quantify the initial control status and the change over time in order to fully understand how a child's function is affected as consequence of the motor involvement and how it could benefit from a specific intervention. The present project was developed from the clinical need of objectively analysing the effects of a specific physiotherapy strategy, Targeted Training (TT) therapy, on trunk control in sitting of children with CP. TT has the advantage of being a therapeutic approach for the management of motor control that uses a sequential cephalo-caudal approach, mimicking the process of normal development [34, 52], which provides a very clear intervention frame. TT also has the benefit of using a well-defined systematic assessment for head and trunk control, the Segmental Assessment of Trunk Control (SATCo) [29]. The starting point for this journey, and thus the main objective of this project, was to develop a clinical tool to objectively measure trunk control in sitting.

The importance of the present project can be seen both from a theoretical and from a practical point of view. In the theoretical part, this work consolidated the concept of motor control developed by Butler and Major [28, 58] and, consequently, supported the SATCo for the evaluation of motor control of children with neuromotor disabilities [29]. From the practical point of view, this project presents the first approach to an objective assessment system for the head and trunk control in sitting, that considers both components of upright postural control, the quantification of alignment of the head and trunk and the classification of the position of the upper limbs for an objective identification of an Open Controlled Kinetic Chain.

Cerebral palsy is the most common motor disability in childhood [4]. Although there is no existing treatment to reverse the brain injury that results in the characteristic motor involvement of CP, there are several physiotherapeutic interventions, as described in Chapter III, that aim at improving gross motor performance (such as Bobath [7, 34], Conductive Education [8, 36],) or improving upper limb function (for example Constraint Induced Movement Therapy [35, 49]). These interventions, despite being widely used around the world, have only generally weak supporting evidence. One of the reasons that makes the evidence of these treatments weak is that the interventions rely on assessments that, although standardised, are subjective; they also infer motor control status from the child's functional activities. Furthermore, these assessments do not consider the separate components of control (alignment of the head and trunk and no external contact of the head-trunk or upper limbs) and so do not present a complete picture of the motor control status of a child with a neuromotor disability. Only the SATCo identifies the specific segmental level of the trunk where control is poor or not demonstrated; it considers both the alignment of the head and trunk and the use of any external support by the child such as hand support [29].

The development of an objective assessment tool that includes these two components of control, is thus of great importance for the validation of different therapeutic interventions, as well as being an ideal complement for the traditional in-clinic evaluations. The developed tool is potentially most advantageous if it can be used in a clinical context, and it thus requires to be 'clinically-friendly', i.e. easy to use for the therapists with minimal disruption to the normal clinical practice routine. Additionally, the tool should be 'patient-friendly', to avoid discomfort and to enable data collection from a wide variety of patients, including the young child and those less able to comply with instruction.

Taking all these above considerations into account, the main method used in the present project was a 2D-video based system. The generation of an objective evaluation method of motor control that followed the guidelines of Butler et al. [29] required the separate development of methods for the assessment of the postural alignment of the head and trunk (Chapter IX) and for the identification of the use of the upper limbs to provide external mechanical support (Chapter X).

Finally, these two components were combined into a tool to define the measured level of control of children with CP (Chapter XI).

The Chapter 'Alignment Study' presents a video-based method to quantify postural alignment of the head and trunk in sitting and to identify deviations from alignment. This study demonstrated how a 2D-video-based system can be used to accurately quantify the aligned posture of a group of adults. The aligned posture was based on a multisegmental model that used the head and trunk segments defined for the SATCo. Although this first study showed that there were some limitations in the quantification of deviation from alignment during movements executed in a plane other than the sagittal plane or when a marker was obstructed (as result of the participant's movement), the main results showed how the calculated error between Dartfish (2D-video-based method) and Vicon (3D motion capture system) could be as small as the inter-assessor reliability. The main contributions that the 'Alignment Study' provides for this work are 1) that the alignment and deviation from an aligned posture of a multisegmental model of the head and trunk can be quantified using a 2D-video-based method; and 2) that these quantifications have small errors when compared to the equivalent data collected with a 3D motion capture system. These findings were further supported by the results of the error calculated between Dartfish and Vicon for the Active and Reactive trials as presented in the Appendix B.

The 'Upper Limb Study' focuses on the second defined component of motor control. This chapter described the potential for an objective method to establish the use of the upper limb to provide external mechanical support to the head-trunk kinetic chain, assuming that the aligned posture already excluded head or trunk support. This study was based on data collected from a group of healthy young adults and a group of children with CP. It showed that assessors have the capacity to make a reliable judgement of the clinical analysis of the upper limb component, independently of the camera view of the participant (frontal or oblique). Findings also show that, despite simplification of the information of the upper limb position (to the hands and elbows only) and of the body (to a cylinder or rectangle covering the head, trunk and pelvis), the presence of an Open Controlled Kinetic Chain (Open-CKC) can be objectively identified. This process can be achieved both with a 3D motion capture system and with 2D-video recordings from a frontal view of the participant. The main lessons from this study were 1) a 2D-video recording contains all the information needed to generate a clinical judgement of the position of the upper limbs in space (i.e. 3D-information); 2) that the simplified representation of the hands, elbows and body reflected the clinical judgement in the identification of an Open-CKC between 45-65%, and that with an optimisation algorithm to modify the minimum clearance distance (threshold) of the hands or elbows to the body, the agreement with the clinical judgement could be significantly improved up to 96%; and 3) that the agreement between the clinical judgement and the objective identification of Open-CKC was maintained when using general threshold values, showing how an automated system (i.e. without needing human input to adjust the threshold to improve the agreement) has the potential to reflect the clinical judgement with large accuracy (70-86%).

Finally, the ‘Levels of Control Study’ Chapter combines the methods developed and lessons learnt in Chapters IX and X. The development of a system to provide a measured segmental level of head/trunk control based on 2D-video recordings of children with CP while performing a SATCo, focused only on the Static element of the assessment. As developed in Chapter IX, the lateral view videos of the participants allowed the generation of a model of aligned posture in sitting for each session, and the calculation of segmental angles in relation to the aligned posture. An oblique view of the children enabled the visual identification of trials where the upper limbs were not used as a strategy to compensate for poor head and trunk control, as developed in Chapter X. The measured segmental level of control was then based on the objective data obtained from the 2D lateral view video using Dartfish. Although the rules defined for the identification of the measured segmental level of head/trunk control did not embrace all the parameters clinicians would use in their assessment, the simplified method presented here is the first approach to the objective identification of the segmental level of head and trunk control in the presence of neuromotor disability.

The main conclusions of the ‘Levels of Control’ study were that 1) the development of a robust tool for the assessment of Static control is an essential starting point; however, 2) it is necessary to include the Active and Reactive tests at each segmental level in order to fully reflect the clinical assessment of motor control; and 3) the development of an automated system for the assessment of control should be based on equipment with the capacity of recording movements in a 3D space and be markerless, making it practical for use in a clinical physiotherapeutic practice.

The work presented in this thesis provides the initial basis for the development of an automated system for the objective assessment of segmental trunk control. The thesis defines how, using 2D-video recordings, the clinical parameters for SATCo tests can be objectively replicated. A clinically-friendly system should consider the advantages of a 2D-video based method, such as the practicality of use in many clinical contexts and with a wide range of patient groups. Exploration of the potential of devices such as Kinect that can provide a value of depth (i.e. 3D data) as well as the 2D image is recommended. Future work should also focus on a markerless system, to minimise the disruption to a clinical assessment, and avoid possible discomfort through the placement and removing of markers. The development of an automated objective system of this type would have value not only in the assessment of head and trunk control of children with neuromotor disabilities but also as a complementary tool for therapeutic assessments of patients with a wide variety of pathologies.

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Appendices

Appendix A. Segmental Assessment of Trunk Control (SATCo)

1. Introduction

The development of the objective methods for the assessment of head and trunk control in sitting as presented in this thesis, was done following the principles of the Segmental Assessment of Trunk Control (SATCo) [1]. This Appendix describes the SATCo in detail based on the publication by Butler et al. [1].

2. Segmental Assessment of Trunk Control (SATCo)

The SATCo is a clinical evaluation tool for assessing the extent of head and trunk control; i.e. it identifies those segments where control is good (is demonstrated) and where control is poor (or is not demonstrated). The classification of control is based on the ability a child has (or not) to maintain an aligned posture of the head and trunk while having the head, trunk and upper limbs free of external contact. The information about the segmental level of control is currently used to identify the head/trunk segment where control training should commence in Targeted Training therapy.

SATCo is based on an approach that considers the many subunits of the head/trunk that must be coordinated to achieve control when in sitting. The subunits or 'segments' are (each) a series of adjacent bones and joints within the trunk. The control of each segment is sequentially assessed in a top-down or cephalon-caudal order. The assessment of the separate segments is enabled through manual support provided by an assistant sitting behind the child. The manual support ensures both an aligned posture of the segments below the trunk segmental level tested and a horizontal orientation of the supported segment; these two elements are essential as they will provide a stable base.

SATCo tests the child's trunk control as a clinical assistant progressively lowers the level of trunk support "from a high level of support at the shoulder girdle to assess cervical (head) control, through support at the axillae (upper thoracic control), inferior scapula (mid thoracic control), lower ribs (lower thoracic control), below the ribs (upper lumbar control), pelvis (lower lumbar control), and, finally, no support, in order to measure full trunk control" (pg. 247) [1] (Figure A-7).

The assessor establishes the status of control at each segmental level through the observation of the child's head and trunk posture in relation to the alignment and the use or not of the upper limbs as a strategy to compensate for poor control. The SATCo test includes three elements of control in sitting: Static, Active and Reactive control. These represent the ability a child has to maintain an independent sitting posture (Static), during active movement (Active or anticipatory) and to restore it after a perturbation (Reactive or compensatory).

3. Instructions[1]

- Child: the child is seated on a bench, feet supported on the ground or on a stable surface and pelvis/thigh position controlled by a strapping system. The pelvis is oriented to neutral relative to vertical.
- Assistant: the assistant should be behind the child, usually kneeling depending on the size of the child and height of the bench. The assistant applies firm manual support horizontally around the trunk immediately below each trunk segmental level tested. The support given should be sufficient to ensure that the trunk is in a vertically aligned posture.

[1] The terminology used in this description has been modified from the original description by Butler et al. [1].

- Evaluator: at each trunk segmental level tested the evaluator encourages the child to ‘sit up tall’ and lift the hands/arms during testing.

The elements of control are tested at each segmental level as follows:

- Static: the child maintains an aligned posture of the head and trunk for five seconds with the hands and arms free of external support.
- Active: by turning the head slowly to each side (>45° or to limitation of range).
- Reactive: by remaining stable during perturbations. Perturbations are generated by a single brisk nudge applied by the evaluator from front (manubrium), from behind (~C7), and from each side (left and right acromion).

The test continues with lowering the support until the child cannot maintain or quickly return to the aligned posture.

3.1 Scoring

At each segmental level tested the presence or absence of control is recorded separately for Static, Active and Reactive control. Butler et al. [1] defined the presence of control by:

- Static: [the child] maintains a neutral vertical trunk posture[2] in the sagittal and frontal planes for five seconds. If the child’s attention is briefly lost, accompanied by a head turn, but a vertical position is maintained, this is still scored as presence.
- Active: may be slight displacement from neutral (<20°) but realigns immediately by most direct route e.g. trunk flexion is corrected by extending to a neutral trunk posture rather than by circling through trunk side flexion.
- Reactive: [the child] will move away from neutral but quickly returns to upright position by most direct route.

[2] Referred to as ‘aligned posture’ of the head and trunk in the present project.

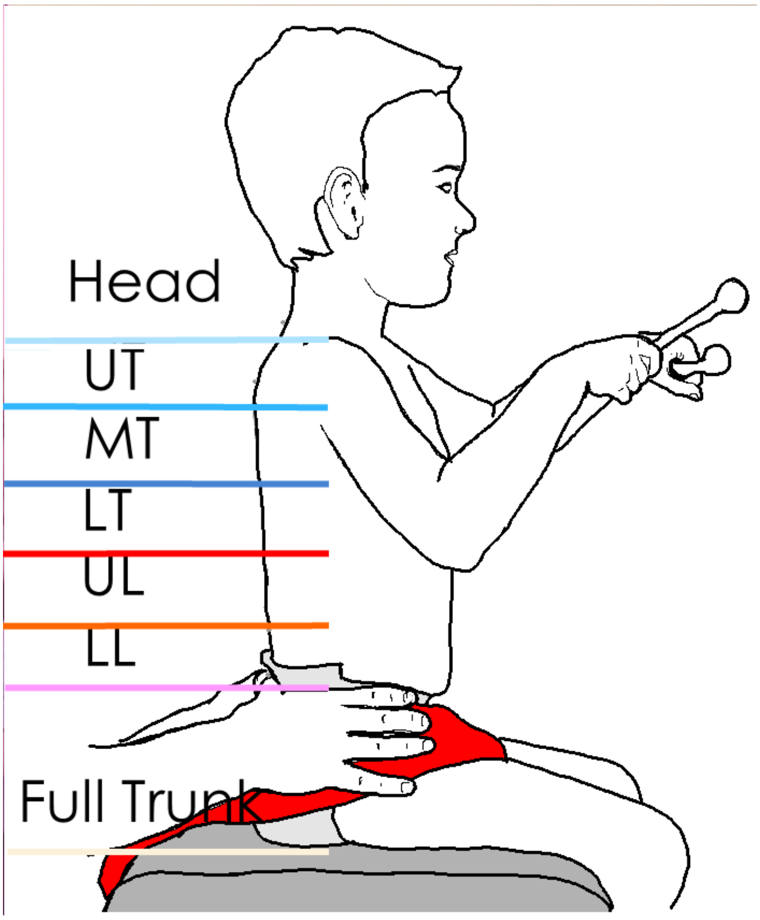

Figure A-7 Representation of the Segmental Assessment of Trunk Control (SATCo) segments.

Showing the distribution of the trunk segments where control is tested: Head (or cervical control) (Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Full Trunk in sitting (tested with no external support). Figure illustrates testing of LL control.

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[1] Butler P, Saavedra SL, Sofranc M, Jarvis S, Woollacott MH. Refinement, reliability, and validity of the Segmental Assessment of Trunk Control. Pediatric Physical Therapy. 2010;22:246-57.

Appendix B. SAR Analysis

1. Introduction

The Segmental Assessment of Trunk Control (SATCo) evaluates the three components of control: Static, Active and Reactive [1]. These components represent the ability a person has to maintain a stable independent sitting posture for a minimum of 5 seconds (Static), during active movement (Active or anticipatory) and to restore it after a perturbation (Reactive or compensatory) [1]. Objective assessment of these three components of control is fundamental to complement the clinical evaluation and to give a complete picture of the trunk control status, in sitting, of a child with a neuromotor disability.

The 2D-video-based method (Dartfish) was validated against a 3D motion capture system (Vicon) for the Static component of the SATCo; detailed results can be found in Chapter IX. This Appendix presents the calculated error between Dartfish and Vicon for the Active and the Reactive components. A group of healthy adults was used for this analysis; this eliminated the complications associated with compromised motor control with children with cerebral palsy and ensure system accuracy and enabled an initial investigation of this aspect of SATCo.

2. Methods

Data from five adults (3 males, 2 females, mean age 28 ±4 years, mean height 1.72m ±0.09, and weight 73.1kg ±10.2), were included for analysis. All the participants wore a tight pair of shorts with men leaving their upper body free of clothing and women wearing a tight vest. Marker placement followed the methods described for the ‘Alignment Study’ (Chapter IX).

A full SATCo test was done starting with testing of Head segmental level and continuing down until Free Sitting. Static, Active and Reactive components were tested following the SATCo guidelines [1]. The clinical SATCo calls the combined head and cervical spine ‘Head’, with the movement coming from the cervical spine. In the present project, the Head (head) and the Neck (cervical spine) were considered as two separated segments.

Data were collected simultaneously using a 3D motion capture system and one video camera. The camera set up for video recordings and for 3D motion capture, was maintained as described in Chapter VIII 'Methods'.

The alignment model values generated from the 'Alignment Study' (Chapter IX). for Dartfish and for Vicon where used for the calculation of absolute segmental angles for each system. The absolute segmental angles of the unsupported segment of each of the Static, Active and Reactive trials were used to calculate the disagreement between signals, which was calculated as the root mean square error (RMSE).

3. Results

The calculated error between Dartfish and Vicon was smaller for the Static trials for all the segments (RMSE 0.14°-2.06°), than for Active (RMSE 0.27°-8.89°) or Reactive (RMSE 2.1°-8.47°); mean error values for each segment are presented in Figure B-.

Figure B-2 - Figure B-3 show separately the calculated disagreement between systems for Static, Active and Reactive. Each figure presents the mean disagreement values calculated for the group of participants for each segmental level tested (Head to Free Sitting). For each segmental level tested only the unsupported segments were included in the analysis.

For the Static trials the calculated disagreement between systems was below 1.5°, except for the Upper-Thoracic segment when testing the Upper-Thoracic segmental level. (Figure B-2). This error is, however, smaller than the values for the inter-assessor reliability of 2.14° as presented in Chapter IX.

For the Active trials the error between systems was higher for the Neck (mean error 8.13°) and Head (mean error 3.79°) segments along all the segmental levels tested (Figure B-1 and Figure B-4). All the other segments had error values between 0.27° and 1.37° for all the segmental levels tested.

The Reactive component is not tested for the head segmental level as the nudges to generate perturbations would be applied below the horizontal hand support. In the present analysis Reactive was not included for the Free Sitting segmental level as it was not tested for all the participants. The Reactive component of the SATCo had larger values for the Upper-Thoracic segment (mean error 6.42°) and the Mid-Thoracic segment (mean error 4.87°) when testing all the segmental levels of control (Figure B-1 and Figure B-3).

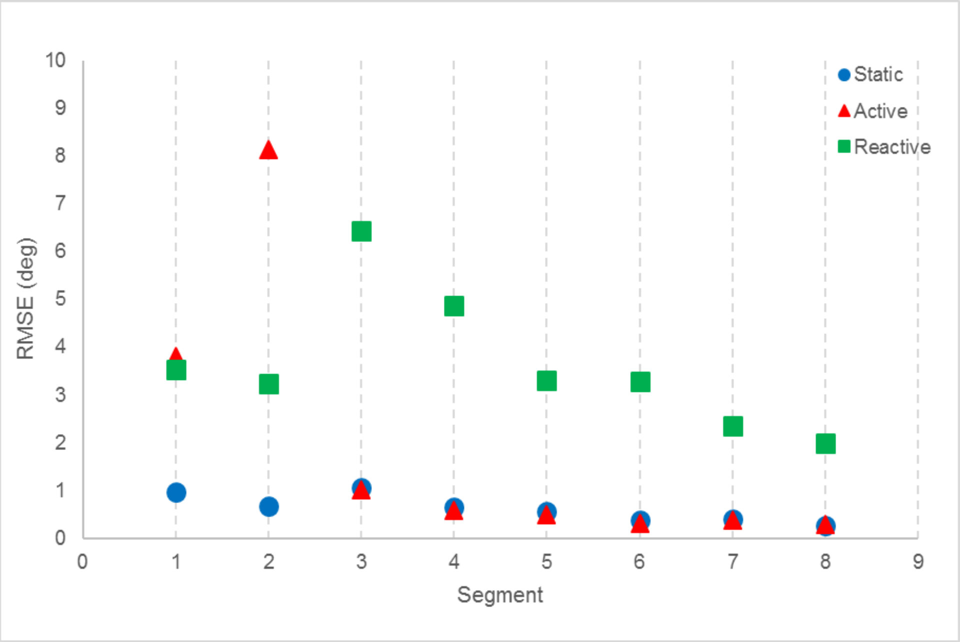

Figure B-1 Static, Active and Reactive mean calculated disagreement (RMSE) in degrees (deg).

Showing the RMSE values for the separate segments (1- Head, 2- Neck, 3- Upper-Thoracic, 4- Mid-Thoracic, 5- Lower-Thoracic, 6- Upper-Lumbar, 7- Lower-Lumbar, 8- Pelvis) for the Static (blue dots), Active (red triangles) and Reactive (green squares) components of control tested during a SATCo.

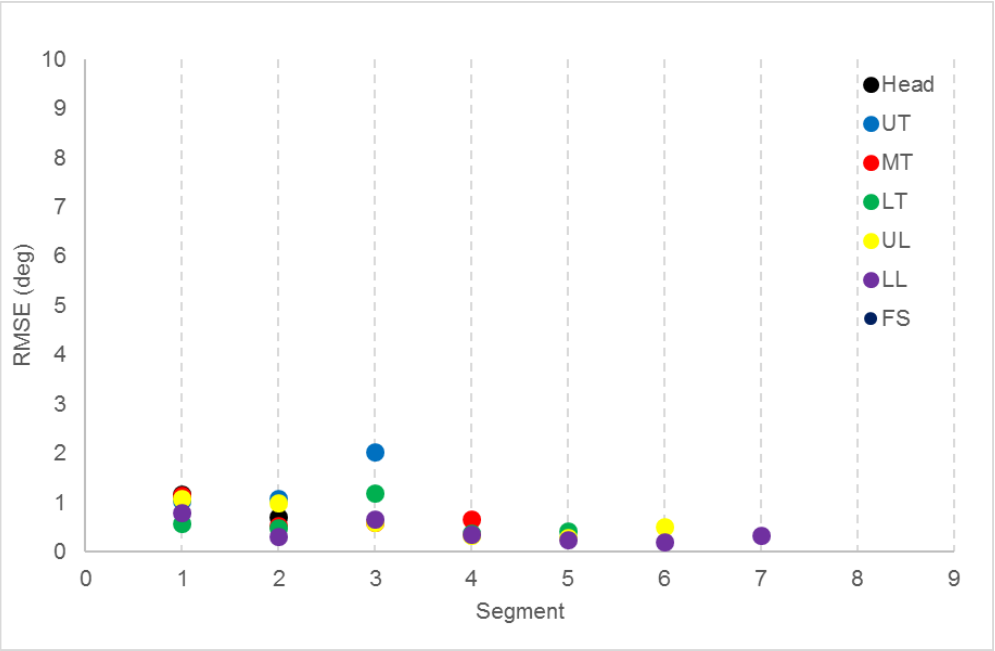

Figure B-2 Calculated disagreement (RMSE) in degrees (deg) for the Static test.

Showing the RMSE values of the unsupported segments (1- Head, 2- Neck, 3- Upper-Thoracic, 4- Mid-Thoracic, 5- Lower-Thoracic, 6- Upper-Lumbar, 7- Lower-Lumbar, 8- Pelvis) for each segmental level tested (Head, Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

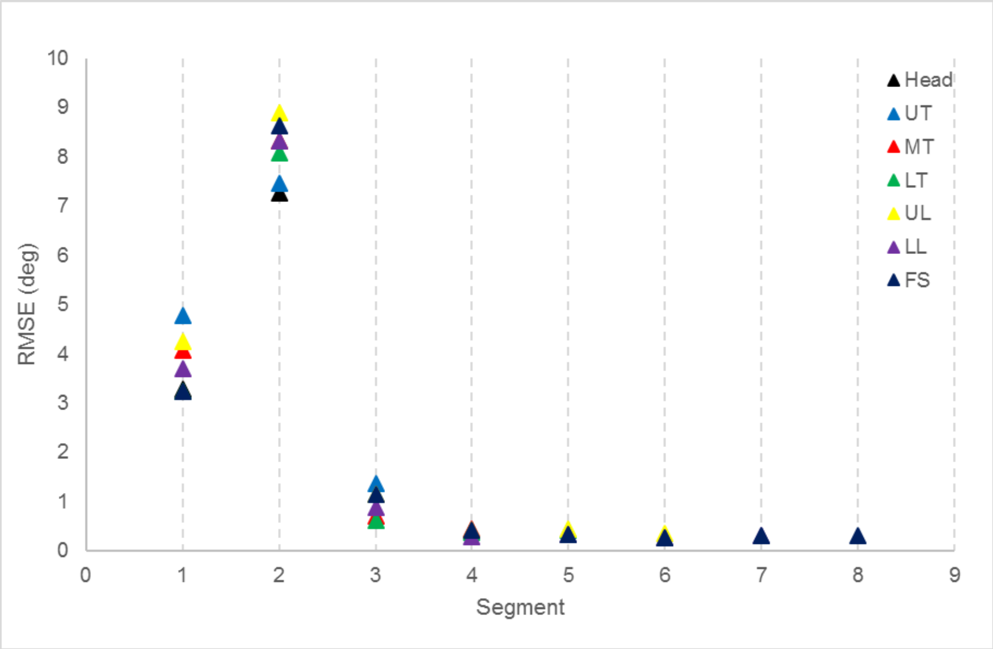

Figure B-4 Calculated disagreement (RMSE) in degrees (deg) for the Active test.

Showing the RMSE values of the unsupported segments (1- Head, 2- Neck, 3- Upper-Thoracic, 4- Mid-Thoracic, 5- Lower-Thoracic, 6- Upper-Lumbar, 7- Lower-Lumbar, 8- Pelvis) for each segmental level tested (Head, Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

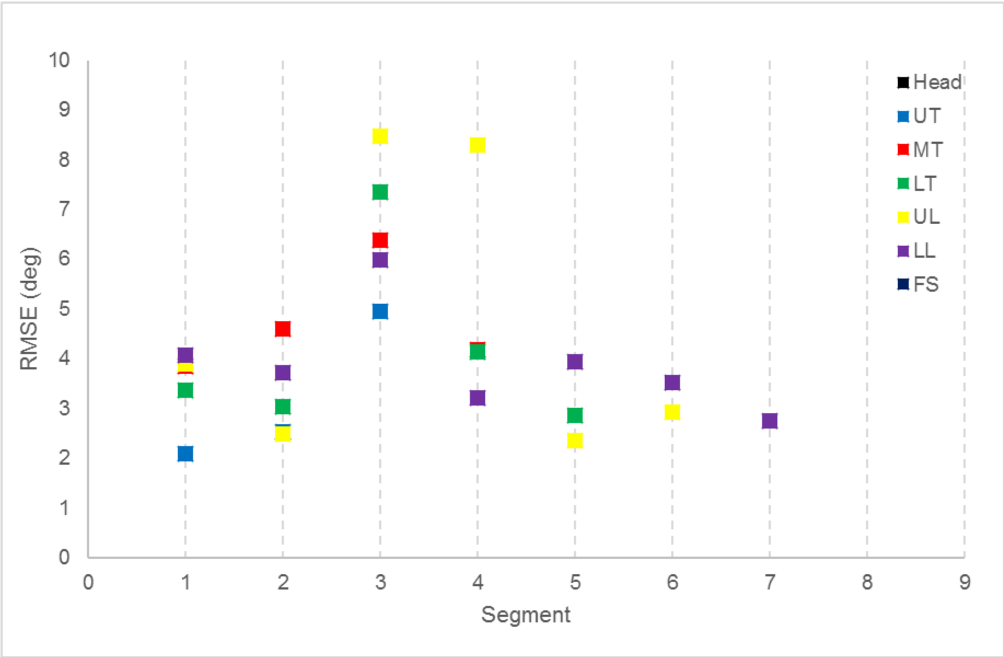

Figure B-3 Calculated disagreement (RMSE) in degrees (deg) for the Reactive test.

Showing the RMSE values of the unsupported segments (1- Head, 2- Neck, 3- Upper-Thoracic, 4- Mid-Thoracic, 5- Lower-Thoracic, 6- Upper-Lumbar, 7- Lower-Lumbar, 8- Pelvis) for each segmental level tested (Head, Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS).

4. Discussion

The results presented in this Appendix showed the calculated error between Dartfish (2D-Video) and Vicon (3D motion capture system) for the Static, Active and the Reactive components of a SATCo.

Although a group of healthy adults was included in this section to ensure system accuracy, there were some elements related to the characteristics of the SATCo that might be the cause of the larger disagreements seen for some segments in the Active and the Reactive trials.

The Static trials provide a reference for the disagreement between the two systems. For the Static trials the participant had to maintain the upright sitting position for 10 seconds. This minimal movement and the clear view of the markers on the participant's head and back are represented in RMSE values that are generally below 2° (Figure B-1 and Figure B-2).

The Active trials required turning the head around a vertical axis to both left and right (>45°). Head turning implied that the head moved across two planes of motion (sagittal and coronal). The video camera used was placed to collect clear data on the sagittal plane and thus movement across two planes resulted in cross talk of the markers that defined the Head and the Neck segments. This was then reflected in RMSE values of up to 8° for these two segments for all the segmental levels tested (Figure B-4). In those segments where there was no rotational segmental movement (Upper-Thoracic to Pelvis) the calculated errors were similar to the RMSE of the Static trials (Figure B-1). This confirms that the quantitative assessment of Active control during a SATCo requires clear data that represents the displacement of the Head and Neck in space. A single 2D-video recording has the potential to provide accurate data for movements in one plane of motion, but to ensure complete information movements should be recorded in more than one plane of motion. This is noted for the further development of a quantitative tool.

Testing the Reactive component of the SATCo required the presence of an extra person (in addition to the participant and the person providing manual support to the trunk as described for the SATCo) in the picture who applied the perturbations by nudging the participant. One nudge was applied from each direction: front (manubrium/sternum), back (~C7), left and right (acromion) in a random order [1]. For the perturbation on the left side of the participant, the C7 and/or T3 markers were partially obstructed by the hand of the person applying the nudge. This implied that for the Reactive trials the traces of those markers had to be manually corrected during the periods of obstruction, as described in the 'Methods' Chapter; this might have generated inaccurate segmental angle calculations for the Upper-Thoracic and Mid-Thoracic segments. The Reactive trials also resulted in head and trunk movement in planes other than the sagittal plane. In the same way as for the Active trials, these movements could generate cross talk of the marker coordinates that finally resulted in larger RMSE values for all the segments (Figure B-3). The higher RMSE between the systems generated by marker obstruction could be potentially overcome by the development of a markerless system.

Although there are difficulties that could be overcome with the use of a markerless system or the use of tools with the capacity to identify and separate the movement of a segment on different planes, the results presented in this section showed that 2D video recordings calculated segmental movement with low disagreement values with a 3D motion capture system for both the Static trials and for sagittal plane segmental movement such as Upper-Thoracic to the Pelvis in the Active trials. Results also showed that the 2D-video-based method has some limitations in the assessment of the Active (Head and Neck segments) and Reactive components of control. Thus, at this time, the results presented in this section, confirmed that the analysis of the measured level of control presented in Chapter XI, should focus only on the Static component of control while further work is done on Active and Reactive measurement. The high agreement between the Dartfish and the Vicon data, as presented here and in the 'Alignment Study', enabled the development of a robust 2D-video-based method to quantify the Static segmental level of trunk control in sitting of children with cerebral palsy as presented in Chapter 'Levels of Control'.

The development of a markerless system for clinical assessments of control would be more 'clinically-friendly' both for the therapists and for the patient. The methods described in this section and through this work, have been based on an assessment developed for children with neuromotor disabilities, but the concept and the quantitative methods have potential for use in other patient groups, such as adults with neurologic conditions such as post-stroke or Parkinson’s disease.

References

[1] Butler P, Saavedra SL, Sofranc M, Jarvis S, Woollacott MH. Refinement, reliability, and validity of the Segmental Assessment of Trunk Control. Pediatric Physical Therapy. 2010;22:246-57.

Appendix C. Manuscripts

1. Manuscripts

- A video based method to quantify posture of the head and trunk in sitting.
- The potential of an automated system to identify the upper limb component of a controlled sitting posture.

2. Published Abstracts

- Posture of the Head and Trunk in Sitting: Quantification Of Alignment.
- Posture of the Head and Trunk in Sitting: Quantification of Head Movement When Testing Segmental Trunk Control.
- Development and Validation of a Movement Evaluation System: Trunk Alignment.

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Full length article

A video based method to quantify posture of the head and trunk in sitting

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ABSTRACT

Maintenance of a vertically aligned posture of the head and trunk in sitting is a fundamental skill that demonstrates the presence of neuromotor control. Clinical assessments of posture are generally subjective. Studies have quantified posture using different technologies, but the application of such technologies in a clinical environment remains difficult. Video recordings, however, are easily used clinically and have potential for quantitative analysis of movement. This study used a video-based method to generate a numerical measure of postural alignment of the head and trunk in sitting. Static and dynamic trials of 12 healthy seated adults were simultaneously recorded with a sagittal video camera and a 3D motion capture system. Segmental angles were calculated for the Head, Neck and six Trunk segments. An agreed definition of aligned static sitting posture agreed was used by five clinically experienced experts to identify video frames where the participants' posture was aligned. The five subsets of frames that defined the aligned posture were combined to give aligned segments (mean ± SD) for each participant. Agreement between experts in the definition (mean) of aligned segmental angles was excellent (ICC = 0.99) and intra-assessor reliability (SD) lay within 2.1°–11.6°. Agreement between the video-based method and the 3D system was below 3.8° and 8.4° for static and dynamic trials respectively. This video-based method allowed the quantification of sitting posture and provided greater detail of the trunk/spinal profile than previous methods. It has potential as a complementary tool, alongside subjective assessments, for patients with a wide variety of pathologies.

1. Introduction

Cerebral Palsy (CP) is a neurodevelopmental condition beginning in early childhood and persisting through the lifespan. It is characterised by a disorder of movement and posture due to non-progressive brain damage; poor motor control of the head and trunk is a common feature [1–3]. Maintenance of a vertically aligned posture of the head and trunk is fundamental to activities such as sitting or standing and requires good neuromuscular control for its achievement. Assessment of postural alignment is thus essential in order to develop an accurate therapeutic plan to target promotion of head and trunk control. During assessments, the trunk is usually considered as a single unit; however, tests such as the Segmental Assessment of Trunk Control (SATCo) [4] (used at The Movement Centre, Oswestry, UK) provides detail of control status of six trunk segments, and of free sitting if a child is able to do so. Although the SATCo has good inter- and intra-rater reliability [4], it remains a subjective assessment in common with visual and other standardised assessments of alignment [5]. Objective quantification is desirable to address the limitations of subjective assessments, to quantify changes in patients that result from therapeutic intervention, or monitor the progression of a neuromuscular condition.

Various methods of quantifying aligned sitting posture are suitable in a research environment. Translation of these methods to a clinical environment is, however, difficult. Three-dimensional (3D) motion capture systems, for example, require the markers to be constantly visible to allow the segment reconstruction. Assessment of head and trunk control in children with CP can often only be achieved with at least two people surrounding the child, especially if the child cannot sit unaided. This inevitably means that some markers are obscured thus affecting accuracy of

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0966-6362/

measurement. Additionally, 3D motion capture systems are expensive with demanding data collection protocols and processing making them impractical in a clinical context. Nevertheless, they remain a ‘gold standard’ for validation of other measurement systems. The most practical clinical method has been the use of video recordings since they require minimal technical and patient preparation and can be used with all ages and severity of disability. The quantification of these video assessments is, however, essential.

This study is part of a wider investigation involving children with cerebral palsy. The aim of the study reported here was to develop a video-based method to quantify seated postural alignment of the head and trunk and to be able to identify any deviation from the aligned posture. To do this we defined the concept of alignment used to assess control, and demonstrated the accuracy of the video-based method against the gold standard for motion capture. We used a group of healthy adults for this preliminary study in order to eliminate the complications associated with compromised motor control and ensure system accuracy. The application to children with cerebral palsy provides one example of the general relevance of this concept and method.

2. Methods

2.1. Ethics

This study was a preliminary technical component to a wider investigation involving children with cerebral palsy. Ethical approval for the complete study was obtained from the NHS Health Research Authority (NRES Committee South Central, United Kingdom) and from the University Ethics Committee. The study was conducted in accordance with the Declaration of Helsinki guidelines.

2.2. Participants

Twelve adults (6 male, 6 female, mean age 27.9 ± 3.5 years, mean height 1.72 m ± 0.08, and weight 71.8 kg ± 11.8) were recruited to the study. All participants were healthy, did not report any fixed bony deformity or other structural problem of the spine, and had a body mass index less than 29 kg m^{-2}. All participants gave written informed consent for participation in this study.

All the participants wore tight fitting clothing; men were asked to leave their upper body free of clothing, women were asked to wear a customised vest that had the back removed. A clear view of the back allowed for more accurate palpation and marking of the spinous processes of the relevant vertebrae for Vicon (Vicon Nexus, Oxford Metrics, Oxford, UK) marker placement, and avoided possible artefacts generated by the movement of clothes.

2.3. Procedures

Participants sat on a bench free of back or arm support. The height of the bench was adjusted to ensure participants’ feet were flat on the floor and the knees and hips were flexed at 90°. Participants were instructed that the initial trial position was with the hands in the air at shoulder height with elbows extended; a common posture used to assess trunk control in children with cerebral palsy. Data recording began before the hands were lifted to the trial position and ended when the hands were placed down again. This ensured that there were no missing data, and that only the data collected with hands in the trial position were analysed.

Participants were asked to sit upright, and verbal and manual feedback was given to achieve an initial aligned posture in sitting. Two different trials were collected, static and dynamic, to replicate physical therapy tests of control. For the static trials, participants were asked to remain still for 10 s in upright sitting with the hands in the trial position. For the dynamic trials, participants were asked to flex, side-flex or extend their head and trunk, returning to upright sitting after a couple of seconds and between each directional movement. This dynamic component enabled video quantification to identify deviation from the aligned posture. Lateral movements were included to represent the clinical situation more fully.

2.4. Apparatus and measurements

Data were collected simultaneously using a 3D motion capture system and one video camera recording sagittal plane movements.

2.4.1. 3D motion capture

Motion data was collected using a ten-camera system (Vicon) at a frequency of 100 Hz. Reflective markers were used to define eight segments (Fig. 1): Head, Neck, Upper-Thoracic (UT), Mid-Thoracic (MT), Lower-Thoracic (LT), Upper-Lumbar (UL), Lower-Lumbar (LL) and Pelvis. An additional marker on the left elbow was used to identify the trial position of the arm. Marker location and segment definition were based on the description of the SATCo trunk segments [4].

Marker reconstruction and gap filling was performed using Vicon-Nexus software (version 1.8.5). Processing was performed using Visual 3D (v.5.01, C-motion, Germantown, MD, USA); a low-pass filter at 6 Hz was used to filter marker trajectories, and segmental angles were calculated. A segmental angle was defined as the angle between a given segment and the absolute coordinate system and was calculated for each of the segments defined. Only the sagittal component of the segmental angles was taken into consideration. Data was exported to Matlab (Mathworks, Cambridge, MA) for further analysis.

2.4.2. Video recording

One video camera (JVC, HD Everio RX110) mounted on a levelled tripod was placed on the left side of the participant at a constant distance of 3.80 m and constant height of 0.90 m. Video was recorded at 25 Hz. Small coloured blocks (2 × 2 × 2 cm) were used to improve the lateral visualization and tracking of the back landmarks (Fig. 1). The blocks were placed 1.5 cm to the left of the equivalent reflective marker. Some of the reflective markers were also used for video tracking.

Coordinates of landmarks from video were obtained using the Dartfish marker tracking tool (Dartfish 7, TeamPro 7.0). The same operator processed all videos. Trunk segments were created using a customised Matlab code, with each segment defined as the vector joining two consecutive landmarks. Segmental angles were estimated and defined within the sagittal plane in relation to the vertical.

2.5. Data processing and analysis

The Vicon and the video signal were synchronised prior to analysis using an initial manual synchronisation followed by an automated fine-tuning using cross correlation.

For both systems, positive angles represented anterior inclination relative to the vertical, and detrended and absolute angles were calculated. The detrended angles (D) showed each angle relative to the mean angle for that trial. The absolute angles (A) for all trials were calculated relative to a single value of aligned angle defined by the participant model of alignment (see below). D angles revealed movement of segments within the trial while excluding drift in position between trials. A angles revealed

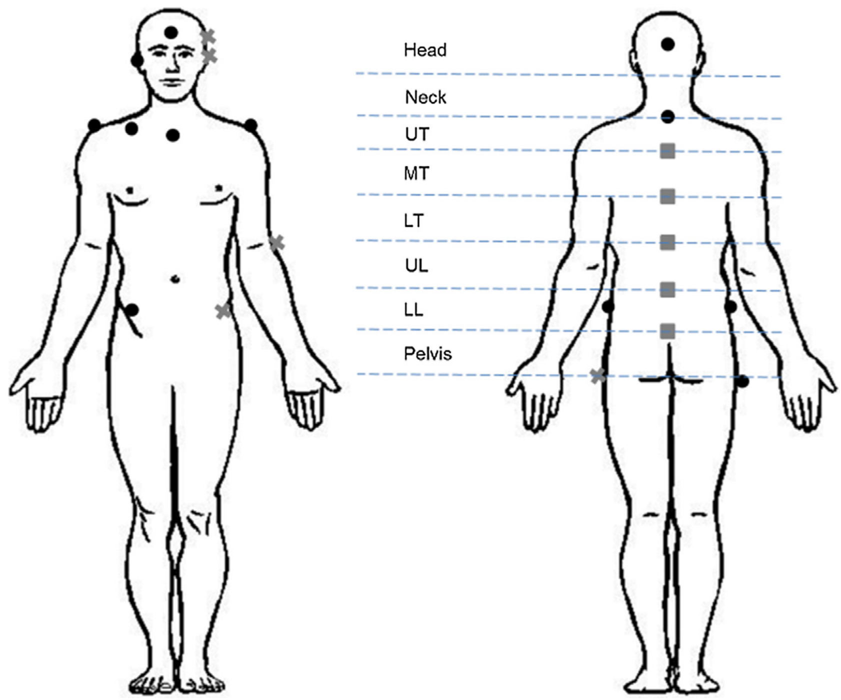


Fig. 1. Marker locations and limits of trunk segments.
Dots show Vicon marker locations: forehead, occipital protuberance, right ear tragus, clavicular notch, middle of the right clavicle, acromion process of the scapula (right and left), spinous process seventh cervical vertebra (C7), iliac crest (left and right), and right anterior superior iliac spine and greater trochanter. Crosses show reflective markers used additionally for Video tracking: left ear tragus, left temporal fossa (in a vertical line from the ear tragus when the head was in neutral position), left anterior superior iliac spine and greater trochanter. Squares show reflective markers that had an equivalent coloured block: spinous process of the third, seventh and eleventh thoracic vertebrae (T3, T7 and T11), third lumbar vertebra (L3) and first sacral vertebra (S1).

position relative to the vertically aligned posture which remained true for the entire session.

2.5.1. Alignment model

The definition of postural alignment in sitting was consolidated in a focus group consisting of four physical therapists, each with 5–20 years of experience performing SATCo and using their standard working practice definition. The model of alignment was then constructed based on this agreed definition and is summarised in Fig. 2. Visual identification of frames where posture was aligned was made from each of the videos. The video rating was performed independently by five clinicians with expertise in posture analysis, following the guidelines illustrated in Fig. 2. The video frames where posture was identified as aligned were then used to obtain the aligned angles for each segment. For each participant, the aligned posture was defined as the set of mean ± standard deviation (SD) values for each aligned segment.

Inter-assessor reliability was tested using a two-way mixed, absolute, average measures intraclass correlation coefficient (ICC 3,1), and calculated as a collective mean SD per segment. For each assessor, intra-assessor reliability is presented as the mean SD values of the identified aligned segmental angles.

2.5.2. Dartfish operator reliability

Dartfish operator (DF-operator) reliability was calculated using the SD between trials. Twelve trials were processed three times with at least 36 h between each processing and segmental angles were calculated. For each set of trials, SD was calculated as a measure of variation and the median value per segment identified. The mean value of the medians for the complete set of videos is reported in Table 1.

2.5.3. Video system validation

The validation of the clinically-based video method was defined as the relative agreement between the segmental angles calculated from Dartfish coordinates and the segmental angles from Vicon. Disagreement was calculated as the root mean square error (RMSE) between the signals. RMSE was calculated for D and A angles.

3. Results

3.1. Alignment model

The aligned posture for each participant was quantified in Vicon and Dartfish. Inter-assessor reliability was excellent for all the segments, ICC = 0.99 with 95% CI (0.99, 0.99) for both systems (Table 1). Mean SD values for the intra-assessor reliability ranged between 2.1° and 11.6°. Combining all participants, intra-assessor variation had greatest values for the Neck and smallest for the UL segment (Table 1).

Fig. 3 presents the sagittal aligned mean angles and range of the Head, Neck and Trunk segments of the group of 12 healthy adults. This model is based on video data only. The combined model of the

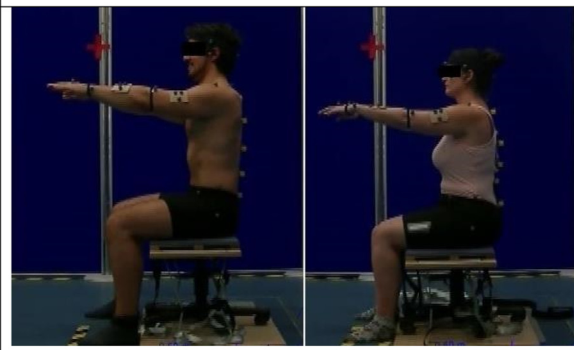
	DESCRIPTION
HEAD AND NECK	Chin: Neither protracted nor retracted
	Eyes: Looking forward
	Ear (tragus): Aligned with the hip
SHOULDER	Shoulder girdle: Neither protracted nor retracted
TRUNK	Smooth and continuous spinal curvatures
	Thoracic spine: Near flat as possible
	Lumbar spine: Slight lordosis or flat
PELVIS	Neutral
LOWER LIMBS	Hip – Knee angles: 90º - 90º
EXAMPLE	

Fig. 2. Aligned static sitting posture.
Qualitative description of the aligned static sitting posture agreed in the focus group and two examples of aligned posture in sitting.

quantified aligned sitting posture of this group of adults was used as reference for the clinical video tracking and validation.

3.2. Dartfish operator reliability

DF-operator reliability varied between $0.86° \pm 0.4$ and $2.13° \pm 0.7$ for all segments. Table 1 shows little variation between segments with least reliability for the Head segment.

3.3. Clinical video tracking

Fig. 4 shows a representative example of a static trial and a dynamic trial. For the static trial the variation of the angles relative to the aligned position (0°) is minimum (<1°); this matched the requirements of the trial described above. From the dynamic test it can be seen that the participant moved away from an aligned trunk posture (4–6, 8–10 and 14–16 s) and then returned to the initial neutral position. This confirms that video recording can be used to track trunk segments. For the Head, Neck and UT segments there was greater movement than for the LT, UL and LL, which is consistent with the anatomical characteristics.

3.4. Video system validation

Table 1 presents the numerical agreement calculated using the root mean square error (RMSE) between the Vicon and Dartfish signals. RMSE for the static trials was below 3° when using the A angles and below 0.5° for the D angles. In both cases the Head and the UT segments showed larger errors (3.76° and 3.31° for A and 1.19° and 0.74° for the D); while the Neck had low errors in both cases (1.61° and 0.37°). The RMSE for the dynamic trials was below 4° for the A and below 3° for the D angles in most cases. The Head and UT had the highest errors (8.35° and 5.9° for A and 7.9° and

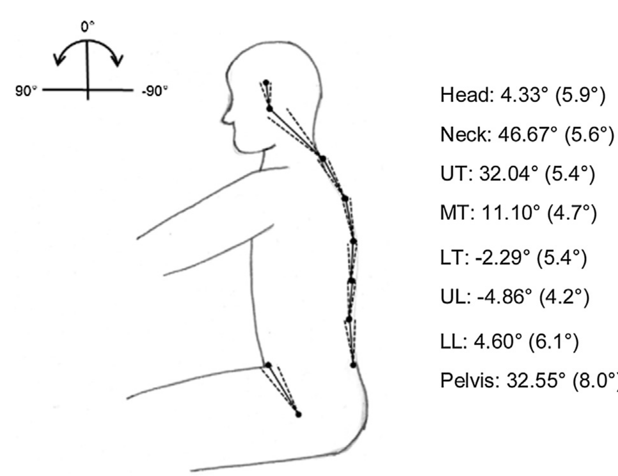


Fig. 3. Representation of the aligned mean position.
Solid and dashed lines show mean and SD segment orientations respectively from all participants.

Table 1
Showing Dartfish operator reliability mean and SD values per segment in degrees. Inter-assessor reliability presented as ICC per segment, and as absolute values presented in degrees. The absolute values are the standard deviation of five assessors' mean aligned values. This is the average from all participants. Intra-assessor reliability presented as the mean SD values in degrees for all participants. Calculated agreement between Dartfish and Vicon: the average RMSE and SD in degrees per segment for static and dynamic trials.

Calculation	Assessor/Trial	General	Head	Neck	UT	MT	LT	UL	LL	Pelvis
DF-operator reliability			2.13° (0.7)	0.86° (0.4)	1.51° (0.4)	0.95° (0.4)	1.15° (0.6)	1.11° (0.5)	1.29° (0.3)	1.01° (0.5)
Inter-assessor reliability (Video)		0.99	0.97	0.92	0.98	0.94	0.98	0.98	0.98	0.99
Inter-assessor reliability (Vicon)		0.99	0.93	0.93	0.97	0.95	0.98	0.99	0.99	0.98
Inter-assessor reliability absolute values			2.03°	2.08°	2.14°	1.85°	1.28°	0.85°	1.29°	0.94°
Intra-assessor reliability	1		7.6°	7.1°	4.4°	5.2°	3.4°	2.2°	3.0°	2.1°
	2		9.0°	10.6°	7.4°	8.7°	5.9°	2.8°	4.7°	4.2°
	3		7.0°	6.5°	4.1°	5.2°	3.7°	2.2°	2.9°	2.5°
	4		8.0°	10.9°	6.8°	7.4°	5.4°	2.8°	4.4°	3.1°
	5		9.6°	11.6°	7.5°	8.9°	6.2°	2.9°	4.9°	4.0°
RMSE Absolute	Static		3.76° (2.3)	1.61° (1.6)	3.31° (2.8)	2.85° (1.8)	3.07° (2.1)	2.77° (1.6)	2.54° (1.5)	3.09° (2.3)
RMSE Detrended	Static		1.19° (0.5)	0.37° (0.3)	0.74° (0.3)	0.38° (0.2)	0.35° (0.2)	0.44° (0.4)	0.40° (0.2)	0.28° (0.2)
RMSE Absolute	Dynamic		8.35° (4.6)	5.50° (2.4)	5.90° (2.3)	2.85° (1.1)	2.48° (1.0)	2.22° (0.9)	2.87° (1.1)	3.53° (1.3)
RMSE Detrended	Dynamic		7.90° (4.2)	5.15° (2.3)	5.41° (2.3)	2.51° (1.0)	2.08° (0.9)	1.77° (0.7)	2.49° (1.0)	2.70° (1.0)

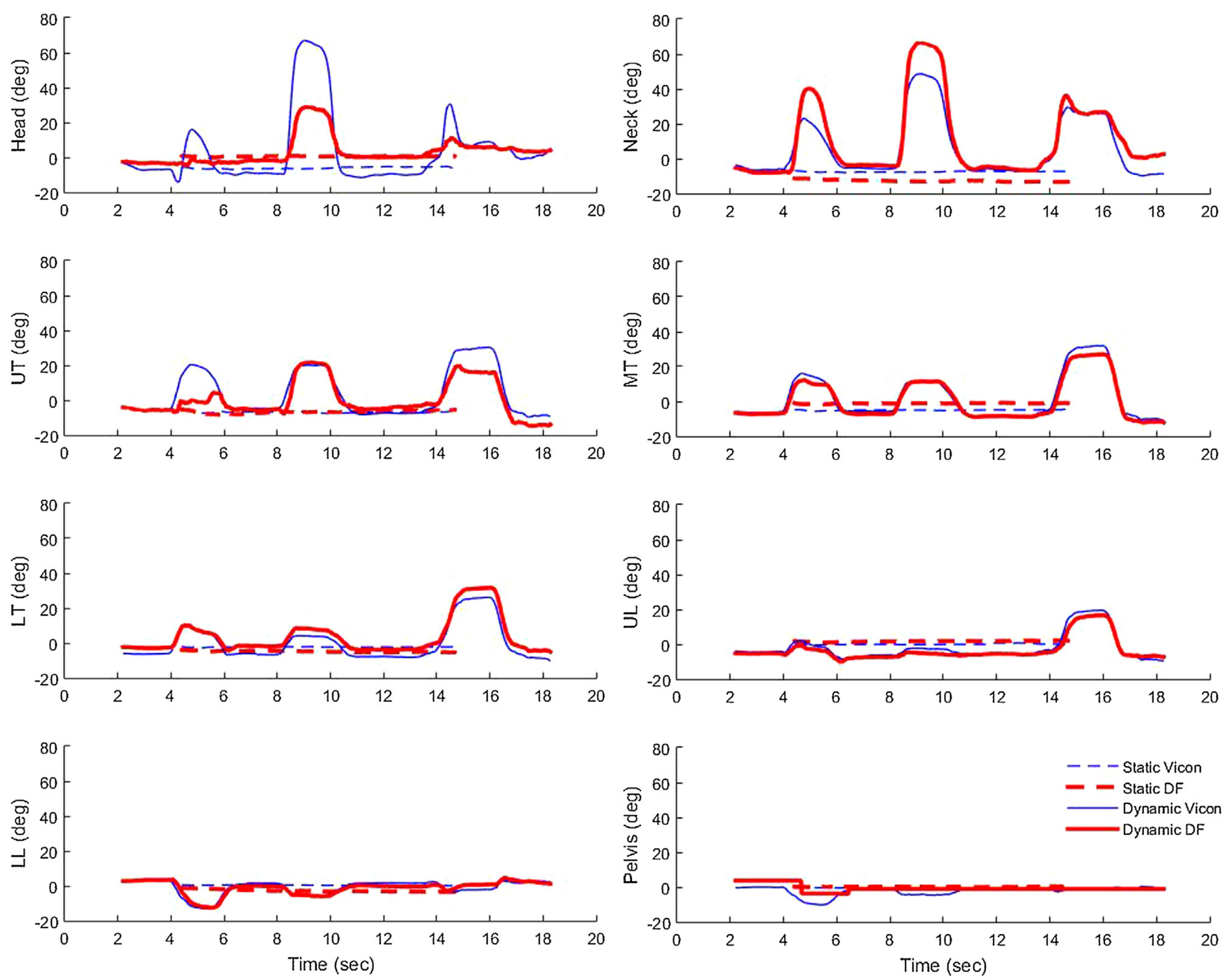


Fig. 4. Representative agreement between Dartfish and Vicon.
Representative example of a time series for segmental absolute angles for a static and a dynamic trial. Dartfish angles (red) and in Vicon angles (blue) for each segment after the hands reached the trial position. The 0° position corresponds to the aligned angle per segment defined in the aligned model. A positive angle refers to flexion and a negative to extension from the aligned angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.41° for D). In contrast to the static trials, the calculation of Neck angles in the dynamic trials showed larger errors (5.5° and 5.15° for A and D respectively).

4. Discussion

This study presents a video-based method to quantify aligned posture in sitting objectively. It includes the validation of this multi-segmental numerical measurement of the head and trunk against the gold standard system for motion analysis for both the maintained aligned posture (static) and for the deviation from alignment (dynamic). A numerical illustration of the aligned posture summarising all participants is presented in Fig. 3.

Previous studies have quantified posture using photographs [6–8], radiographs [9–11], rastersterography [12–14] and three-dimensional (3D) motion capture systems [15–18]; most of these have value and application in research, but are rarely practical in a clinical setting. Although Curtis et al. [16] based their 3D model on the seated SATCo [4], the trunk is usually considered a single rigid segment from the iliac crests to the shoulders [17,18], or the trunk posture is described using a general trunk angle, a cervicothoracic angle and a lumbar angle [7–11]. The calculation of separate segmental angles for the thoracic and lumbar region, as presented in this study, however, reveals detail of the spinal profile. This can be a determinant factor in the generation of a universal model of alignment as it allows the consideration of anthropometric differences.

The development of a video-based method suitable for clinical use was achieved using a video analysis system (Dartfish) and a customised code (Matlab) to track and calculate the angular displacement of the separate segments. This method has the advantage of presenting an outcome measure that is similar to the human observation of posture. Interpretation is closer to the pre-existing assessment processes used in clinical physical therapy practice. Video recorders are used commonly in clinical practice, in contrast to more complex technologies used to measure spinal angles. The videos were used to obtain angle traces that were visually equivalent to those calculated with the 3D motion capture system. Nevertheless, there were some difficulties generated by the software operation and by the inherent characteristics of the video.

Video processing required a considerable amount of manual interaction; the operator had to actively select the marker at the beginning of the trial and then manually correct the trajectory of the marker as needed. Despite reaching values of 2.13°, the DF-operator reliability was smaller than the intra-assessor reliability (Table 1). A limitation of video is that obstruction of a marker results in a compromise of marker coordinates for the duration of the obstruction. Processing of this period of marker obstruction was achieved by inferring its position based on the position of other markers and anatomical landmarks. Use of a single plane sagittal video simplifies clinical operation. This limitation implies that translations or rotations in one or both of the coronal and transverse planes, which are commonly present in clinical assessments, will result in movement artefacts which over or underestimated the displacement of a segment. This was found in the Neck and of the Head and UT segments respectively (Fig. 4). For those movements performed in a true sagittal plane, however, the Dartfish tracking of the markers was close to the Vicon tracking. Clinicians should be aware of this planar anomaly but the overall value of the quantification of sagittal movement will outweigh this factor and should be addressed in future work.

The calculation of the error between Dartfish and Vicon was based on two different angle calculations, absolute (A) and detrended (D) angles. Differences between the two systems are larger for the dynamic trials than for the static trials for both A and D angles; this is associated with the plane of motion in which the movements were executed and the differentiation of movements in only the sagittal plane (automatic in Vicon but requiring visual judgement for the videos). For the static trials, the RMSE was under 1.5° for the D angles; this means that, in relation to the real fluctuations of the angles, both systems were similar irrespective of the participant's position. As a consequence, Dartfish can measure change in angle for static trials, but A angle across an entire session is less reliable (e.g. 3.76° for the Head A angle vs 1.19° for the D angle). For static and dynamic trials, the RMSE was generally smaller than the intra-assessor reliability values (Table 1).

Assessment of aligned posture is the starting point for many neuro-physical therapy strategies but, to date, could not be quantified in a clinical setting. The work presented here is an essential component for development of this complementary tool for the assessment of segmental trunk control. Furthermore, it provides validation sufficient to justify future development of an automated processing system suitable to be used in a clinical setting. A video based method has potential for use with patients with a wide variety of pathologies such as children with cerebral palsy, adult stroke or neuromuscular conditions. It does not require active patient co-operation or understanding and is suitable for use in a clinical environment. Continuous recordings of assessments can complement other clinical outcome measures and support the traditional subjective assessment of posture.

5. Conclusion

This study has demonstrated the accuracy of a video based method for objective quantification of clinically identified postural alignment of the head and trunk in sitting. These preliminary results provide a basis for future studies. This has shown to be more accurate and reliable than the subjective judgment, with the added merit of giving a numerical value. In addition, the use of a segmental approach gives the advantage of greater detail of the spinal profile. This method thus has potential as a complementary tool alongside subjective assessments for patients with a wide variety of pathologies.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2016.10.012.

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Full length article

The potential of an automated system to identify the upper limb component of a controlled sitting posture

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ABSTRACT

Full trunk control in sitting is demonstrated only when the head-trunk are aligned and upper limbs remain free of contact from mechanical support. These components represent a Controlled Kinetic Chain and can be evaluated in people with neuromotor disability using the Segmental Assessment of Trunk Control (SATCo) when a therapist provides manual trunk support at different segmental levels. However, the SATCo, as with other clinical assessments of control, is subjective. The SATCo was translated to objective rules relating the position of the hands and elbows to the head-trunk and then tested to determine the extent to which this automated objective method replicated the clinical judgement.

Clinical evaluation used video to determine whether the upper limb was free of mechanical support while the objective evaluation used 3D motion capture of the trunk and upper limbs with a classification rule. The agreement between clinical and objective classification was calculated for three conditions of a distance-from-support-surface threshold parameter in five healthy adults and five children with cerebral palsy.

The unfitted (zero-threshold values) method replicated the clinical judgement in part (68.26% ± 15.7, adults, 48.3% ± 33.9 children). The fitted (level-of-support determined) agreement showed that the process could be refined using trial specific parameters (88.32% ± 5.3 adults, 89.84% ± 10.2 children). The fixed-values agreement showed high values when using general group parameters (80.80% ± 3.1 adults, 74.31% ± 21.5 children).

This objective classification of the upper limb component of trunk control largely captures the clinical evaluation. It provides the first stages in development of a clinically-friendly fully automated method.

1. Introduction

Independent unsupported sitting, with a vertically aligned head and trunk (head-trunk) is a milestone of typical development and requires full motor control of the head-trunk [1]. Reduction or absence of head-trunk control can result from neuromotor disability such as cerebral palsy (CP) with the consequent lack of independent sitting ability leading to functional limitations [1].

The head-trunk is a kinetic chain of segments comprising the head and neck and successive trunk segments to the pelvis. These axial segments branch into the upper limbs. The term 'Controlled Kinetic Chain' (CKC) denotes the biomechanical chain as a controlled entity and is used in the context of determining the neuromuscular control status of individual joints within that chain [2]. In independent unsupported sitting, full motor control of the whole kinetic chain of the head-trunk and upper limbs is demonstrated only when there is no end of range mechanical support at any axial joints or from external objects other than the primary support surface. This control without mechanical support is termed an Open-CKC [2]. In the trunk, a sitting posture that is, for example, slumped into full lumbar flexion with passive end of range mechanical support from intervertebral ligaments obviates the need for active control; it is termed a Closed-CKC [2]. This closure is assessed clinically by analysis of trunk alignment [3]. Use of the upper limbs or an external object to support the trunk mechanically can also remove the need for active control and is also termed a Closed-CKC [2]. This closure is assessed clinically by observation of the upper limbs in relation to the trunk and external objects. For example, if a person rests one hand on his/her thigh, then this can help maintain a sitting posture in the presence of poor trunk control even if the trunk is apparently aligned.

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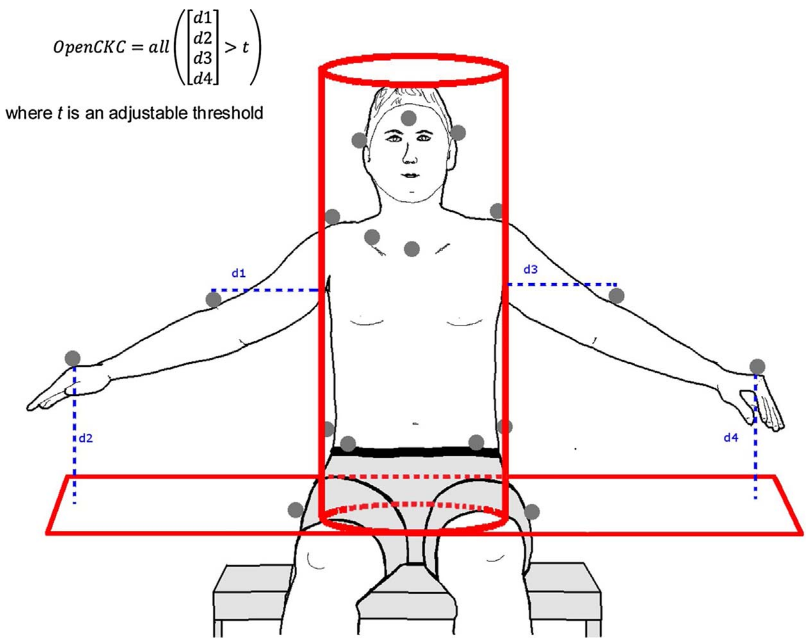

Fig. 1. Marker locations and supported-volume.
Dots show Vicon marker locations: forehead, middle of the right clavicle, left and right acromion process of the scapula, lateral condyle of the humerus (elbow), head of the third metacarpal bone, Iliac crest, anterior superior iliac spine and greater trochanter. The red cylinder and plane represent the volume that defined a Closed-CKC. Dashed blue lines show the shortest distances ($d_{1\text{-}4}$) from each of the hands and elbows to the supported-volume surface for this given posture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Assessment of trunk control should thus consider both alignment of the head-trunk segments and use of the upper limbs. In neuromotor disability such as CP, motor control is usually assessed through comparison with typically developing children and inferring control status from functional activities [4,5] or through a child's ability to maintain a balanced posture either statically and/or dynamically [6,7]. The Segmental Assessment of Trunk Control (SATCo), uniquely assesses CKC status at six trunk segmental levels and free sitting [3]. Although it provides greater information about motor control strategies, in common with other clinical tests, it is subjective. Objective quantification is desirable since it is repeatable, eliminates variability between and within assessors and offers the potential for quantifying clinical changes over time. In order to complement a clinical assessment, an objective automated system should incorporate the rules existing in the specific clinical test. It should also be practical for clinical use and thus 'clinically-friendly' for both for the child and the therapist.

A method for quantifying postural alignment in sitting has been developed that uses a video-based system [8]. The aim of the study reported here was to explore the potential for an automated method to establish use of the upper limb component of the CKC. This was achieved by: (i) defining the clinical rules to assess the upper limb kinetic chain status through video recordings; (ii) formulating a method to replicate the clinical rules with quantities that could be measured and classified objectively; and (iii) testing the extent to which the objective method replicates the clinical judgement. Initial development was performed with a group of healthy adults to eliminate the complications associated with compromised motor control. The system was then tested in a real clinical context with a group of children with CP.

2. Methods

2.1. Ethics

This study was a preliminary technical component to a wider investigation. Ethical approval for the complete study was obtained from the NHS Health Research Authority (NRES Committee South Central, United Kingdom) and from the Manchester Metropolitan University (MMU) Ethics Committee. The study was conducted in accordance with the Declaration of Helsinki guidelines.

2.2. Participants

Two groups of participants were recruited: an adult group (Adult-group) of 3 males, 2 females, mean age 28 ± 4 years, mean height 1.72 m ± 0.09, and weight 73.1 kg ± 10.2 tested at MMU; and a child group (Child-group) of 4 males, 1 female, mean age 8.4 ± 4.62 years, mean height 1.1 m ± 0.27 and weight 24.16 kg ± 10.8 tested at The Movement Centre (TMC, Oswestry, Shropshire, United Kingdom). All adults were healthy with a body mass index < 29 kg m^{-2}. All children had a diagnosis of cerebral palsy and were participating in Targeted Training (TT) therapy at TMC. All adults gave written informed consent for their participation. Children's parents provided written informed consent with child assent where possible. To allow accurate palpation of anatomical landmarks for marker placement, adults wore a tight pair of shorts with men leaving their upper body free of clothing and women wearing a tight vest. Children wore only their underwear, nappy or shorts as usual for their clinical assessments.

2.3. Procedures

All participants sat in an upright aligned posture on a bench free of back or arm support. The height of the bench was adjusted to ensure each participant's feet were flat on the floor with knees and hips flexed at 90°. Adults performed a sequence of twelve arm movements that represented both no-support, such as both arms in the air to the sides or the front, and support/contact such as hands on the bench, legs or head. Six trials were recorded per participant with different segmental levels of trunk control tested (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and free sitting, FS) following the SATCo guidelines [3]. The trunk was supported manually directly beneath the tested segment resulting in 'unsupported segments' above the manual support: arms (tip of the fingers to axillae), head and unsupported segments of the trunk.

Children were recorded during the routine SATCo performed as part of their TT therapy.

2.4. Apparatus and measurements

Data were collected simultaneously using a 3D motion capture system and one video camera.

2.4.1. 3D Motion Capture

Motion data was collected using a ten-camera system (Vicon Nexus, Oxford Metrics, Oxford, UK) at a frequency of 100 Hz. Reflective markers were used to define the Head, Trunk and Pelvis segments, and to track the position of the right and left Elbow and Hand (Fig. 1). Hands and Elbows were selected as representative upper limb landmarks.

Marker reconstruction and gap filling used Vicon-Nexus software (version 1.8.5). Processing was performed using Visual 3D (v.5.01, C-motion, Germantown, MD, USA); marker trajectories were lowpass filtered at 6 Hz. Data was exported to Matlab (Mathworks, Cambridge, MA) for further analysis.

2.4.2. Video recording

Video was recorded at 25 Hz from one video camera (JVC, HD Everio RX110) mounted on a levelled tripod placed directly in front of the Adult-group at a constant distance of 3.90 m and constant height of 0.90 m. For the Child-group the camera was placed at right diagonal front (approximately 45°) to allow the parent to stand in front of the child without obstructing the camera view. The camera was at a constant distance of 2.5 m and a constant height of 0.75m. Either front or oblique views are permissible for SATCo.

A second lateral view camera was used to confirm those trials where the head-trunk was vertically aligned and only those trials were processed.

2.5. Data processing and analysis

The Vicon and video were synchronised prior to analysis using an initial manual synchronisation followed by automated fine tuning using cross correlation.

2.5.1. Clinical identification of Open-CKC

The clinical classification of CKC status was performed by five clinicians familiar with this process (5–20 years of daily use). Assessors followed a defined clinical rule to assess the upper limb kinetic chain status from video recordings. This rule was: a Controlled-Kinetic-Chain is open when there is no contact between an unsupported segment and any other part of the body or any external objects. ‘Contact’ includes firm or light touch; ‘external objects’ include the supporting bench, toys, parent’s hands and the hands supporting the trunk. Definition and assessment of the aligned posture in sitting has been described elsewhere [3,8].

Open-CKC frames were identified from both the adult and child videos and frame numbers exported to Matlab for further analysis. The collective classification of all assessors was calculated by the mode classification for each frame.

Inter-assessor reliability was tested using a two-way mixed, absolute, average measures intraclass correlation coefficient (ICC 3,1) for each group. Intra-assessor reliability was tested for one of the assessors with 49 randomly selected videos from both groups.

2.5.2. Automated identification of Open-CKC

For the automated (Vicon) classification of Open-CKC the classification rule was simplified to the location of four markers (both hands, elbows) in relation to the body and supporting bench. The body was represented by a 3D cylindrical volume covering the head-trunk and pelvis, and the bench was defined as the volume below the trochanteric markers (Fig. 1). These two volumes were termed ‘supported-volume’. The shortest distance from the hands and elbows to the supported-volume was calculated by customised Matlab code (Fig. 2-A, B). An Open-CKC was present when all distances (both hands and elbows) were > t mm, where the threshold (t) was an adjustable parameter (Figs. 1, 2-C, D). Three methods for setting t-values were used: (i) $t = 0$ (unfitted); (ii) adjusting t using an optimisation routine to maximise agreement with the collective clinical assessment (fitted); and (iii) using generalised fixed values not requiring assessor judgement (fixed-values).

2.5.3. Agreement between clinical and automated methods

The agreement between the automated and the collective clinical classification of Open-CKC was calculated as the percentage of time during which the classifications were the same for each trial (Fig. 2-E, F). For comparison, the mean percentage agreement between individual assessor and the collective clinical classification was also calculated.

Statistical difference between processing agreement methods was calculated with a repeated measures ANOVA for each group. The differences between segmental levels for each group was assessed using a univariate analysis for each processing method.

3. Results

Twenty-nine Adult-group trials and 52 Child-group trials were analysed separately.

The clinical inter-assessor consistency of Open-CKC identification was excellent for both groups (Adult-group ICC = 0.96, Child-group ICC = 0.95). Intra-assessor reliability was also excellent (ICC = 0.89).

The unfitted, fitted and fixed-values clinical v automated agreements calculation were significantly different between methods (68.26% ± 15.7, 88.32% ± 5.3 and 80.80% ± 3.1 mean ± SD respectively for unfitted, fitted and fixed-values) for the Adult-group ($F_{1,23} = 260.36$ $p < 0.001$) and for the Child-group (48.3% ± 33.9, 89.84% ± 10.2 74.31% ± 21.5 as previous) ($F_{1.32,92} = 41.07$, $p < 0.001$) ($F_{1.32,92} = 41.07$, $p < 0.001$) (Fig. 3-A).

The clinical v automated agreements (unfitted) were significantly different ($p \leq 0.001$) between the UT and all the other segmental levels in the Adult-group, and between the UT and MT, LL and FS (both $p < 0.05$) for the fitted processing (Fig. 3-A). There were no differences for the fixed-values processing. In the Child-group there was no significant difference between segmental levels for any of the agreement methods (Fig. 3-A).

For the fitted agreement the optimal t-values are presented in Fig. 3-B. The Adult-group shows larger t-values for the UT (190.8 mm) and MT (186.6 mm) segmental levels while the Child-group shows larger t-values for the UT (113.7 mm) and LT (83.8 mm) segmental levels. This information was used to define the threshold values for the fixed-values agreement at 200 mm for UT and MT segments, 100 mm for other segments in Adult-group and 150 mm for the UT segment and 50 mm for all other segments in the Child-group.

4. Discussion

The full classification of a Controlled-Kinetic-Chain (CKC) requires knowledge of both head-trunk alignment and the position of the upper limbs. This study investigated the methods required to translate the clinical classification of the upper limb component of a CKC into an automated objective method suitable for application in a physical therapy practice for example with children who have CP.

An objective automated system should incorporate the subjective rules that are already embodied within the existing clinical practice. It should also be ‘clinically-friendly’ and not disrupt the normal practice routine, it should be ‘child-friendly’ (i.e. preferably without adhesive markers) and able to collect clean data within a crowded (visual) environment. Finally, an objective system should be simple for clinicians to use. This study has taken the first steps towards a clinically-friendly objective automated measure by: (i) making explicit and then testing a precise formulation of the clinical rules; and (ii) exploring whether a reduced, minimum set of rules could objectively replicate the clinical classification.

Results showed that the clinician intra- and inter-assessor reliability was excellent with either a frontal view (Adult-group) or an oblique view (Child-group). Humans can extract 3D information from a single camera view and extracting this full 3D information automatically will be technically challenging. Thus, the next step taken in this study was to determine the minimum 3D information that might be required by an

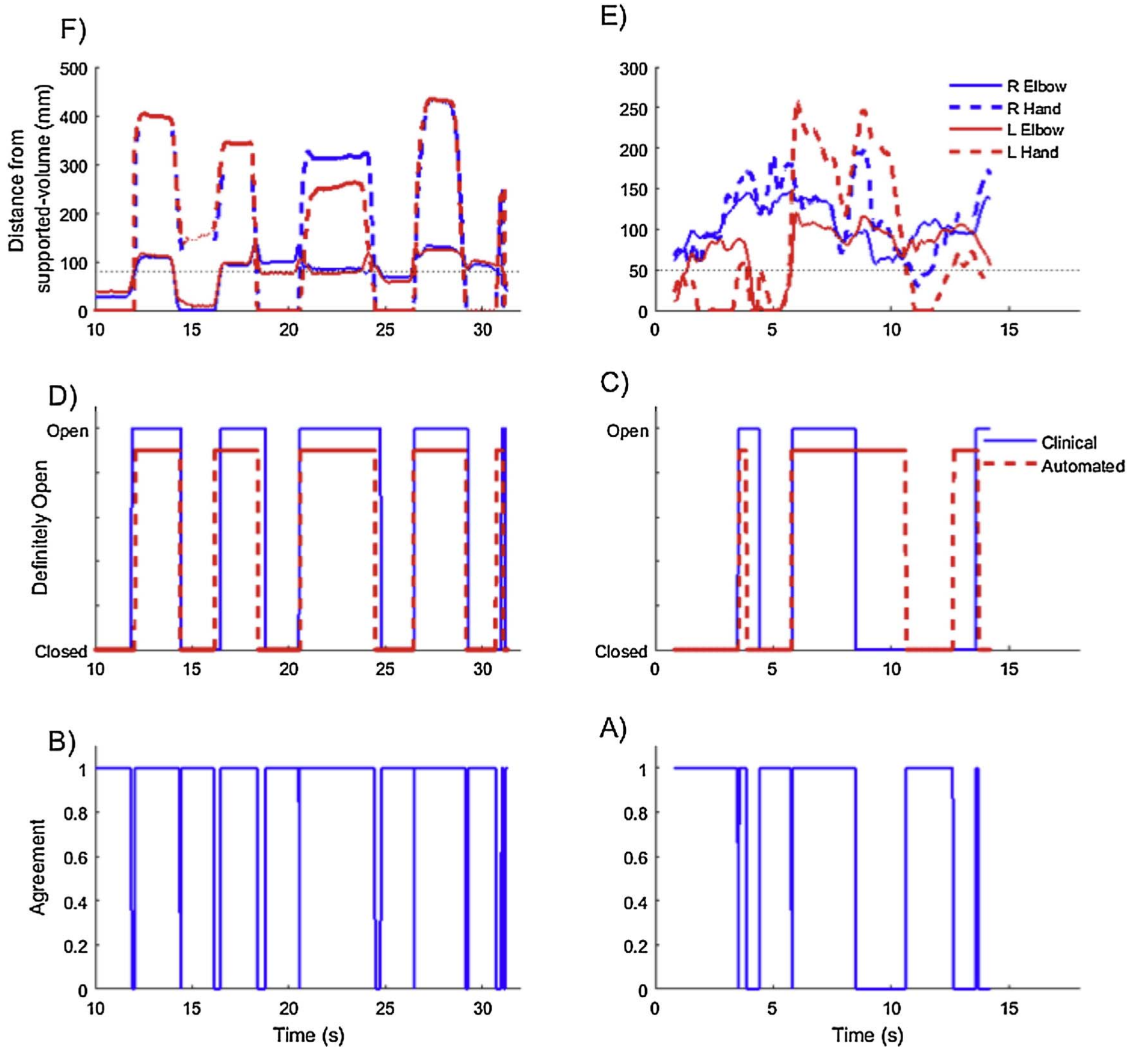

Fig. 2. Representative examples of the automated tracking of the upper limb, classification of Open CKC and calculated agreement over time.
Showing a representative trial example for the Adult-group (panels A,C,E) and Child-group (panels B,D,F). (A,B) Automated tracking of the upper limb (left, red line; right, blue line) shows the position of the hands (dash) and elbows (continuous) relative to the supported-volume. The black dotted line shows the t-values used for calculations. (C,D) Classification of the Open-CKC for the clinical (blue line) and the automated (dash red line, reduced height for visibility) assessment using the fitted method for the adult and the fixed-values method for the child. (E,F) Shows the agreement between clinical and automated classification (92.4% for the adult. 68.5% for the child). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

automated system.

This study describes two groups of participants. These groups differ so widely that it was inappropriate to consider the Adult-group a ‘control-group’; the Adult-group, however, served in the initial development to eliminate the complications associated with compromised motor control.

Results for the unfitted method showed that it was possible to classify Open-CKC v Closed-CKC using only the positions of the participant’s hands and elbows in relation to the supported-volume. However, the relatively low percentages of agreement between clinicians and this simple method, particularly at higher levels of support, were a clear indication that this method was not capturing sufficiently what clinicians observe from video.

Results for the fitted method showed that the agreement with the clinical judgement improved substantially by adding a single adjustable parameter. This parameter (t) increased the thickness of the supported-volume, incorporating the supporting hands and ensuring clearance with the participant’s body. The t-value was adjusted to maximise agreement with the clinical assessment. Furthermore, a larger t-value, particularly at higher levels of support (UT and MT), matched better with the clinical assessment. This implies that during a SATCo to test UT segmental level, the clinician’s hands providing trunk support also potentially provide external mechanical support to the upper limbs. An Open-CKC is only demonstrated when the upper limbs are clear by a margin of error represented by values required for t.

Applying parameter t without using clinical assessment was tested in the fixed-values method. Results showed that it was possible (more than 70% agreement), to replicate the clinical judgement using fixed values of t that were participant invariant and level of segmental support specific. Using general values in this way implies that the method is fully automated i.e. clinical judgment is not needed to modify the t. However, this study used relatively small groups of participants; increasing the number of participants could help to refine the general t-values and increase the fixed-values reliability. Furthermore, it remains possible that this automated rule could be improved further using participant specific measurements.

The work developed in the present study used a 3D motion capture system to support the concept. There are, however, several difficulties with this system. A clinician can detail the volume of the upper arm and see its relation to the supporting hands or the participant’s body and can distinguish the presence of light touch that results in a Closed-CKC. A clinician can also easily identify external supporting elements from

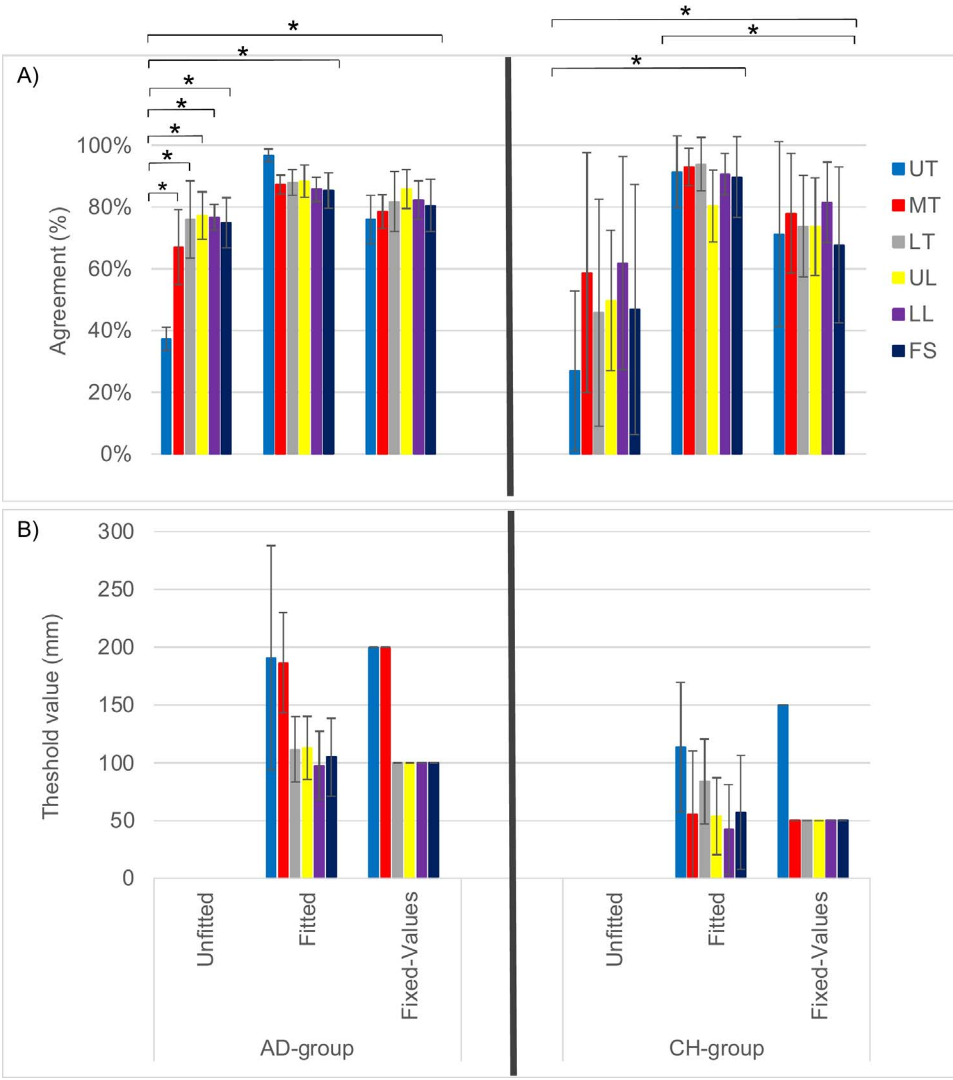

Fig. 3. Calculated agreement between the human and the objective identification of Open-CKC.
(A) Showing the mean collective percentage of agreement for the Adult-group (AD-group) and the Child-group (CH-group) for all processing methods (unfitted, fitted and fixed) and the standard deviation (error bars). Agreement is presented separately for each segment tested (Upper-Thoracic, UT; Mid-Thoracic, MT; Lower-Thoracic, LT; Upper-Lumbar, UL; Lower-Lumbar, LL; and Free Sitting, FS). +Indicates significant difference, $p < 0.05$. *Indicates strong significant difference, $p < 0.001$. (B) Showing threshold values for the fitted and the fixed agreement calculations of the various segments.

video such as a child's contact with parents' hands. In contrast, the 3D system was based on a simplified model of the upper arms and, even if this model was more complex, it would still be difficult for a 3D motion capture system to identify light touch. Furthermore, external objects can only be recognised by a 3D system if they have reflective markers.

This assessment overall (alignment and CKC status) will measure the head/trunk control demonstrated by a child. It is known that typically developing infants achieve independent sitting between 6 and 8 months of age [9]. The full assessment of alignment and CKC status will allow measurement of this process in typical development and of the emergence of trunk control in children with CP; this may lead to greater understanding of control elements related to immaturity and/or to dysfunction. The children in this study could be showing trunk control that is primarily related to their dysfunction but this cannot be stated definitively at this stage of development of the quantitative and automated tool. Although the position of the hands and arms in relation to independent sitting has been studied before both using video analysis [10] and a 3D motion capture system [11], the analysis was related to symmetrical or asymmetrical reaching and to the qualities of reaching and manipulation. As far as could be determined from the literature, the use of the upper limbs to compensate for poor trunk control in sitting has not been previously studied.

This study has demonstrated that the upper limb component of a CKC can be identified objectively and that it matches with the clinical judgement. The shortcomings of a 3D system have also been identified. These difficulties can be overcome by the development of a video-based system using the factors established in this study to complement clinical assessments in neurodisability such as cerebral palsy.

5. Conclusion

This study addressed the classification of Open-CKC required for the clinical assessment of trunk control status in children with cerebral palsy. Results demonstrated that, if a participant is sitting with an aligned head-trunk, a frontal or oblique camera provides sufficient information for clinicians to make a reliable, objectively supported, clinical analysis of upper limb Open-CKC in children with cerebral palsy. The automated objective method reduced the clinical judgement to measurement of the position of the participant's hands and elbows in relation to a defined supported-volume of the head-trunk using a 3D motion capture system (Vicon). While this simplified objective measure was less robust than the clinical judgment it demonstrates the main rules required to analyse Controlled-Kinetic-Chain status and thus justifies future investment in application of advanced image analysis techniques to enable automatic CKC classification in a clinically-friendly method.

Conflict of interest

None.

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ABSTRACT - POSTURE OF THE HEAD AND TRUNK IN SITTING: QUANTIFICATION OF ALIGNMENT

Introduction

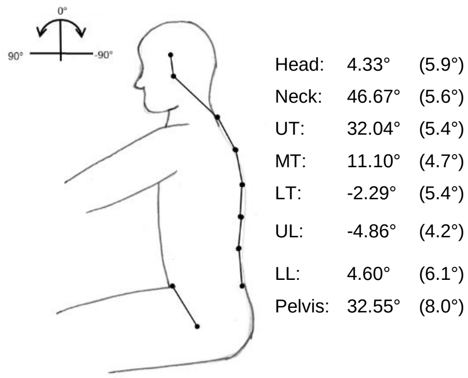
Posture can be assessed either subjectively or objectively. In the literature there are detailed subjective descriptions of ‘ideal alignment’ in standing but no agreement of an ‘ideal seated postural alignment’. The use of radiographs [1, 2], rastersterography , and three-dimensional (3D) motion capture systems have addressed many of the limitations of subjective postural assessments, but are rarely practical in a clinical setting. Video recordings are easily used clinically but also have potential for quantitative analysis of movement. This study used a video based method to generate a numerical definition of postural alignment of the head and trunk in sitting.

Methods

A definition of aligned static sitting posture was agreed in a focus group. Participants (4 male, 4 female, age 27.2±3.25 years) sat upright on a bench. Static and Dynamic trials were recorded simultaneously with a 3D motion capture system and a video camera recording sagittal plane movements. The agreed definition was used to visually identify video frames where posture was aligned. Angles of Head, Neck, Upper, Mid and Lower-Thoracic, Upper and Lower-Lumbar and Pelvis segments were calculated in relation to the absolute coordinate system and used to construct a model of alignment from aligned frames. This clinically based video method has been previously validated against segmental angles calculated from the 3D motion system using the RMSE (ms. under review).

Results

For each participant, a segmental model of quantified aligned sitting posture was defined as the set of mean ± SD values from videos. A combined model for the group is shown.



RMSE for the Static trials was below 3° and for the Dynamic trials was below 4° in most cases.

Discussion

Our study presents a multisegmental numerical model of aligned posture in sitting using a video based method. However, the small sample size is insufficient to generate a universal model.

Previous studies [1, 2] have measured angles for the complete thoracic region (36°±12 and 40.60°± 10 respectively). The addition of our mean angles for the UT, MT and LT gives a resultant angle of 45.43°, which is comparable to previous results. For the lumbar region our study revealed much smaller values which is consistent with reports in the literature describing a decreased lordosis curvature while sitting.

This multisegmental method of quantification of sitting posture gives greater detail of the spinal profile than previous methods. It has potential as a complementary tool alongside subjective assessments for patients with a wide variety of pathologies.

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QUANTIFICATION OF HEAD MOVEMENT WHEN TESTING SEGMENTAL TRUNK CONTROL

Introduction

Trunk control is fundamental for effective functional activity in neuromotor disability [1]. In contrast to other subjective tests that consider the trunk as a single unit the Segmental Assessment of Trunk Control (SATCo) assesses discrete segmental levels [2]. Furthermore, the SATCo includes Static, Active and Reactive control giving a more complete picture. The SATCo is conducted in sitting with firm horizontal support directly beneath the tested trunk segment. It tests six segmental levels (Head through Lower Lumbar) and free sitting. This study measured Head motion during a SATCo to give an objective quantification of a subjective assessment.

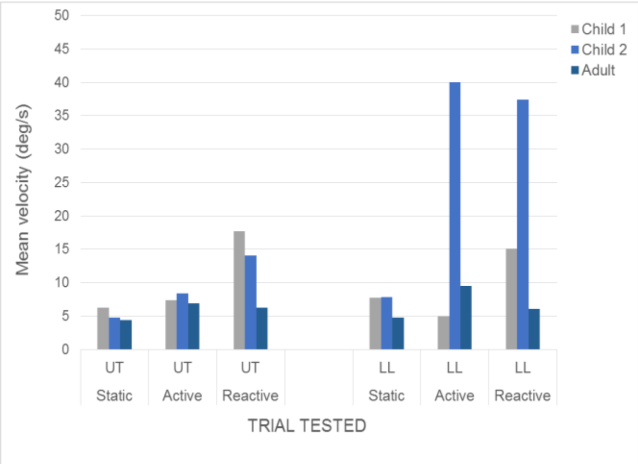
Methods

One healthy adult (27y) and two children with different degrees of neuromuscular disability (4y1m, 4y5m) were tested using the SATCo. Child 1 was learning to control his trunk without external support. Child 2 was learning to control his trunk with external support at waist level.

A video camera additionally recorded sagittal plane movements. Markers were placed on the ear tragus and temporal fossa in vertical line with the ear when the head was aligned. These were used to define a Head segment. Head segmental angles were calculated in relation to a real vertical. Cumulative displacement from the vertical normalised by time was calculated for each trial.

Results

Head motion during testing of Upper-Thoracic (UT) and Lower-Lumbar (LL) segments are shown in Figure 1.



As expected, the Adult showed only small Head displacement throughout. Larger values for the Reactive tests are a clear indication that Child 1 is still acquiring full trunk control. The poor lumbar control of Child 2 is clearly demonstrated and contrasts with Child 1 for the Active and the Reactive tests.

Discussion

The results show how increasing task complexity (Static to Reactive) and reducing the level of segmental support (UT to LL), increases Head motion in the presence of a neuromotor disability. This is consistent with the subjective valuation of the SATCo.

Previous studies have quantified Head motion of typically developing children in relation to the level of support during quiet sitting [3, 4] showing 2.3°/s for unsupported sitting [3] and 18° for thoracic support and 30° for pelvic support [4]. However, the methods used by Curtis [3](3D motion capture system) and Rachwani [4] (magnetic tracking sensor) are difficult and costly to use in a clinical setting. Our video based method is clinically practical with minimal disruption to the clinical session.

Quantification of an assessment complements the subjective findings and provides validation for any changes observed over time.

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Keywords:

Trunk alignment, movement control, 3D motion capture, video analysis

Title:

Development and validation of a movement evaluation system: trunk alignment (Poster)

ABSTRACT – Work in progress

Background and need for the project

A primary objective of physiotherapy for adults and children with problems of movement control is to enable or restore function in an upright posture to facilitate sitting, standing and, if possible, walking. This helps independence and self-esteem. Targeted Training (TT) is a physiotherapy technique used at The Movement Centre (TMC), Oswestry. It seeks to promote postural control in children with cerebral palsy (CP) from a perspective that is based on the biomechanical requirements to execute daily activities. TT is founded in the premise that motor control learning can be simplified if the child with CP has to learn and refine the control of only one segment of the body at a time while the rest of the non-fully controlled segments are stabilised using an external support (Butler, 1991).

Quantified, objective tests of function are rare in neurophysiotherapy, as many of the main characteristics of postural control are not easily measured and thus most of the measurement outcomes remain subjective. Motion capture systems that can provide a quantitative measure of movement have been used in children with CP mainly for gait analysis (Butler et al., 1992), to illustrate the ability to reach an object (Rachwani et al., 2013), or to describe quiet sitting (Murans et al., 2011). These studies have generally taken the trunk as one rigid segment from the anterior superior iliac spines of the pelvis to the acromioclavicular joints. Nevertheless, the characteristics of the vertebral column

confer a wide range of mobility to the trunk, and the morphologic differences between the vertebrae allow the distinction of sub-segments within the trunk. Although assessment of postural alignment is common in neurophysiotherapy, there is no agreed definition of 'neutral vertical posture'.

The aim of this study is thus i) to define neutral vertical postural alignment in a way that can be quantified and then ii) to develop a clinical tool that will allow an objective measurement of postural control through the quantification of alignment when the participants are not using their arms for support.

Method

Following precise definition of 'neutral vertical postural alignment' using anatomical landmarks, a 2D tracking system is used to quantify the location of landmarks on the back of the participants that represent the different levels targeted with the TT method. This uses videos collected from a lateral view of the participants, from where the specific analysis of alignment is made taking account of the relationship between the different segments and the relationship to vertical. Simultaneously, a 3D motion capture system is used as a validation method.

Clinical potential of the research

The development of an objective tool that can be used on a routine basis in the clinical environment has great potential to evaluate the outcome of physiotherapy and of other interventions in CP related to control of posture and functional abilities. A successful outcome of this study also opens the possibility of using the objective tool to evaluate the effects of therapy for other conditions and age groups. This could have a major impact in physiotherapy practice by enabling, for the first time, the objective quantification of the effects of a specific intervention or combination of interventions, and could potentially help to better understanding of the rehabilitation processes.

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