Kinematic analysis of the upper limb during anatomical and functional movements in healthy children

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Kinematic Analysis Of The Upper Limb During Anatomical and Functional Movements in Healthy Children.

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Impairments of upper limb function can negatively impact an individual's ability to carry out everyday tasks. Children with cerebral palsy can have limitations of upper limb movement due to physiological and structural changes in their body. Current treatment regimes for children with upper limb involvement of cerebral palsy are assessed using a variety of qualitative assessment tools. These measures rely on subjective input from the assessor, and can be insensitive to significant functional improvements.

Research methods in upper limb motion analysis are developing towards use as clinical tools. To date, there is a paucity of knowledge on the quantitative measures of range of motion (ROM) and function of upper limbs in healthy children. There is also lack of agreement on repeatable functional tasks of the upper limb for 3D measurement. The identification of a repeatable task in healthy children would facilitate the use of upper limb 3D motion analysis to guide clinical practice and improve patient outcomes.

This thesis aims to describe upper limb joint range of movement in each degree of freedom and present normative three dimensional kinematic data of upper limb movement in healthy children during a repeatable upper limb functional task. This will provide a basis for comparison to children with movement disorders for future research and clinical practice.

The UNSW kinematic upper limb model was found to successfully measure three dimensional upper limb anatomical and functional movements in healthy children. Normative kinematic data are reported for anatomical movements and two functional tasks.

The results of the studies undertaken showed that differences in dominant and non-dominant limbs were present during anatomical and functional movements. Joint angles measured were found to be repeatable in healthy children. The results suggest that methods used were reliable for investigating upper limb kinematics. Functional movement time-series data were found to be repeatable for the group with the exception of wrist flexion/extension during the hand to mouth movement for both the dominant and non-dominant limbs.

These findings improve current knowledge on upper limb kinematics in healthy children. This knowledge can assist the investigation of movement disorders in children to facilitate clinical decision making.

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ABSTRACT

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TABLE OF CONTENTS

List of Tables

List of Figures

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Upper limb function is important for independent functioning (Magermans et al., 2005). Impaired function of the upper limbs can restrict performance in basic everyday tasks (Garcia-Alsina et al., 2005). The World Health Organisation's International Classification of Functioning, Disability and Health (ICF) states that various conditions with neuromusculoskeletal involvement, for example cerebral palsy, post-stroke and traumatic brain injury, can impair functions of the upper limbs. Children with cerebral palsy, in particular hemiplegic cerebral palsy, often have limitations of upper limb movement (Eliasson et al., 1998) due to physiological and structural changes in their body as a result of a brain injury that occurred before, during or shortly after birth (Fitoussi et al., 2006).

Current treatment regimes for children with upper limb involvement of cerebral palsy include splinting, intensive training therapies of the affected limb, constraint therapies of the unaffected limb, chemodenervation and orthopaedic surgery (Rodda and Graham, 2001). A variety of qualitative assessment tools have been developed to measure upper limb impairment and document the effects of treatment (Bourke-Taylor, 2003, DeMatteo et al., 1993, House et al., 1981). These measures rely on subjective input from the assessor and can be insensitive to significant functional improvements (Ramos et al., 1997, Mackey et al., 2006). Quantitative measurement of upper limb impairment before and after treatment can provide objective information to the clinician about the specific way a child uses their upper limb functionally, assess the effects of treatment regimes and feed back to clinical decision making.

Quantitative analysis of lower limb function in children with cerebral palsy, via instrumented three dimensional gait analysis is commonly used worldwide and has proven to be a very useful tool to assist clinical decision making (Rau, 2000). Measurement of lower limb movement patterns using three dimensional gait analysis pre and post surgery have indicated to clinicians that some procedures that were previously thought to be appropriate, were in fact detrimental to patient function. These findings have consequently led to changes in techniques for treating certain gait abnormalities (Rodda et al., 2006) and the identification of gait patterns using three dimensional gait analysis has been associated with specific treatment regimes for optimal outcome (Rodda and Graham, 2001). The use of three dimensional gait analysis in clinical settings has provided quantitative data to characterise the function of gait in healthy populations. With comparison of pathological gait to normative data, advances in knowledge of how to treat the lower limbs of children with cerebral palsy have followed (Rodda and Graham, 2001).

There is a potential for use of three dimensional motion analysis in the upper limbs in populations with movement limitations to assist treatment planning. To date there is limited knowledge of upper limb kinematics during functional tasks. Some work has been done to develop three dimensional motion analysis protocols for the upper limb (Buckley, 1996). It is imperative that clinical decisions for treatment (especially irreversible interventions) are based on how children commonly use their upper limbs in activities of daily living. A repeatable upper limb movement needs to be identified so that three dimensional motion analysis for the upper limb may be reliable and meaningful. Three dimensional motion analysis of upper limb movement may allow classification of movement patterns during functional tasks and provide quantitative data on how upper limbs function without pathology. This knowledge would provide a basis for comparison to pathological movement to assist in treatment decision making.

There have been conflicting findings reported previously regarding dominant/non-dominant limb differences in producing a given movement.

Previous research using goniometry has shown between-limb differences in upper limb motion in adults, with the dominant limb demonstrating reduced range of motion (ROM) compared to the non-dominant limb (Gunal et al., 1996). Previous research using three dimensional motion analysis for the upper limb in healthy children has reported no significant differences between dominant and non-dominant limbs of kinematics during functional tasks (Mackey et al., 2006). It is therefore difficult to determine whether there is a difference between the dominant and non-dominant limb movement of healthy children when measured with three dimensional motion analysis during previously studied upper limb movements.

1.2 Statement of the Problem

To date, there is a paucity of quantitatively measured ROM and function of the upper limbs in healthy children. There is also a lack of agreement on a repeatable functional task of the upper limb for three dimensional measurement, such as gait is to the lower limb. The identification of a repeatable task in healthy children would facilitate the progression of three dimensional motion analysis in the upper limb for use of this technology in the clinical setting (Gutierrez-Farewik et al., 2006, Rau, 2000). This would enhance current knowledge on healthy child upper limb function from a biomechanical perspective and provide a basis for comparison to children with movement limitations in future research and clinical practice.

1.3 Aims

This thesis aimed to investigate the repeatability of upper limb anatomical movements and functional tasks and provide a normative dataset of three dimensional upper limb kinematic data in healthy children.

1.4 Objectives

The following objectives were set to achieve the aims of this thesis:

1. Measure the kinematics of upper limb anatomical movements and functional movements of the shoulder joint in 3 planes; elbow joint flexion and extension; forearm pronation and supination; wrist joint flexion and extension; and wrist joint radial and ulnar deviation.
2. Conduct three dimensional motion analyses of upper limb anatomical and functional movements in a healthy child population, employing the University of New South Wales (UNSW) upper limb kinematic model (McIntosh et al., 2002).
3. Report the anatomical joint ROMs in upper limbs in healthy children.
4. Describe kinematics of two functional movements (moving the hand to the mouth and moving the hand over the head).

5. Investigate the repeatability of successive performances of anatomical and functional upper limb movements in healthy children.
6. Identify any differences between dominant and non-dominant limbs.

1.5 HYPOTHESES

The following hypotheses were addressed in this thesis:

1. Healthy children perform reproducible upper limb maximum joint angles over repeated measures during three dimensional motion analysis measurement of anatomical movements.
2. Healthy children perform reproducible upper limb peak joint angles over repeated trials during hand to mouth and hand over head functional movements.
3. The timing of peak joint angles during hand to mouth and hand over head functional movements are reproducible in healthy children.
4. Joint angles throughout the two functional movements measured are reproducible over multiple repeats in healthy children.
5. There would be no difference between the dominant and non-dominant limb of healthy children when measured with three dimensional motion analysis during anatomical and functional upper limb movements in a healthy child population.

1.6 LIMITATIONS

The maximum joint angles of shoulder internal and external rotation were measured using two separate anatomical movements. External rotation was measured by rotating the humerus outwards while kept close to the trunk. Humeral internal rotation was measured by asking the children to place their hand behind their back. The children were instructed to allow their elbow to drop forward while their hand was behind their back to maximise the amount of internal rotation of the shoulder. Based on this protocol, it is assumed that the maximum joint angle of shoulder joint internal rotation was measured during the movement of the hand behind the back.

The large ROM that the upper limb joints moved through can result in increased skin movement relative to underlying bone. Use of markers placed on the skin to describe the position of the underlying bone is subject to skin movement artefact (Roux et al., 2002). This introduces greater measurement error than that encountered when studying the lower limbs, which move through smaller ranges (Schmidt, 1999, Rau, 2000). This error was minimised by placing the markers on bony prominences (Rau, 2000) and marker placement was done by one person for all subjects.

Participants were asked to perform specific anatomical movements that were designed to elicit maximum ROM at each upper limb joint. It was assumed that the measured upper limb maximum joint angles during anatomical movements in healthy children would be representative of the active ROM available at each of the upper limb joints in each plane of motion.

1.7 DELIMITATIONS

Surgical treatment to improve lower limb function is generally performed between the ages of 10 to 12, preceding skeletal maturity. Therefore, a child population was chosen for this thesis as it was anticipated that the protocols established here would be used to assist in surgical treatment planning for children with movement limitations. It is possible that interventions used to improve any movement limitations may be most beneficially employed before skeletal maturity, to decrease the adverse impact of disease on growing bones, and to minimise movement limitations and the need for surgical bony correction. To make the information gained useful for treatment decision making, subjects recruited into the study were delimited to 8 to 12 years of age.

It was necessary to ensure that the children were following instructions during the movement execution. During the recording of the anatomical

ROM movements, the children were given verbal encouragement to reach their maximum joint angles. The children's movements were also observed, and visually critiqued. When it appeared that the children failed to reach maximum joint angles (for anatomical movements) or perform the functional tasks as demonstrated, the child was asked to repeat the movement until the observer was satisfied that the requirements of the movements were met.

1.8 Thesis Outline

Chapter one introduces background information for the thesis, in addition to the statement of the problem, aim and objectives of the thesis and hypotheses tested. Chapter two reviews the current literature on cerebral palsy, methods of upper limb assessment and the need for kinematic investigations in upper limb movement. Chapter three describes the methods and preliminary investigations of the protocol used. Chapter four presents the first experiment; measuring anatomical movements to determine maximum joint angles for all degrees of freedom of the upper limb in healthy children. Repeatability and effects of limb dominance are examined. Chapter five describes a study of peak joint angles and timing of the peak joint angles during two functional tasks in healthy children. Repeatability and effects of limb dominance for these functional tasks are investigated. Normative graphical representations of the two functional upper limb tasks are also presented and discussed. Chapter six summarises how the hypotheses and aims of the thesis were addressed and draws final conclusions.

CHAPTER TWO

REVIEW OF LITERATURE

Human upper limbs are used frequently in daily living for a large variety of tasks such as self care and feeding. Movement impairments of the upper limbs can affect a person's ability to function independently (Garcia-Alsina et al., 2005). The presence of musculoskeletal deformity and altered innervation that result from cerebral palsy can impose functional restrictions on the upper limbs (Eliasson et al., 1998). Therefore, this review of literature will define cerebral palsy, discuss the current methods for assessing movement limitations, introduce the techniques to be used in this thesis and discuss published findings of those techniques in different populations.

2.1 CEREBRAL PALSY

The description and definition of cerebral palsy is complex and has been adapted since its original description by Little in 1861 (Rosenbaum et al., 2007). The term cerebral palsy is used to describe a wide range of symptoms derived from varied pathology, cause and prognosis (Blair and Watson, 2006). It is the outcome of a brain lesion that occurs prenatally, at birth or shortly following birth (Graham and Selber, 2003). In 2004, an

International Workshop on Definition and Classification of Cerebral Palsy was held to refine the definition of cerebral palsy for health care professionals (Rosenbaum et al., 2007). The current definition was developed from this meeting and was published in the Definition and Classification of Cerebral Palsy, April 2006 Report (Rosenbaum et al., 2007):

> *"Cerebral palsy describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to nonprogressive 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".*

By definition, the primary cause of cerebral palsy is not progressive, as the lesion is static. The specific causes of these lesions have not been identified to date (Reddihough and Collins, 2003). The injury causes abnormal innervation (heightened or diminished) to muscles by the damaged upper motor neurons. This results in musculoskeletal pathologies including muscle shortening, bony torsion, joint instability and degenerative arthritis (Graham and Selber, 2003). These pathologies are known as secondary effects of cerebral palsy, which are progressive with typical growth and development (Graham and Selber, 2003).

2.1.1 Prevalence

The true incidence of cerebral palsy is not measurable due to the delay in symptom presentation after birth and the loss of cases through death or migration (Stanley et al., 2000). The prevalence (rate of neonatal survivors within the population) of cerebral palsy is 2-2.5 live births per 1000 (Stanley et al., 2000). In Australia, the estimated number of people living with cerebral palsy in 2007 was 33,797, with 8,784 aged 19 years and under (Economics, 2008). Based on this report by Access Economics, which states that spastic type cerebral palsy comprises around 80% of all cerebral palsy cases, the estimated number of children (aged 19 years and under) in Australia with spastic type cerebral palsy in 2007 was 7,027.

2.1.2 Classification

Classification of cerebral palsy can be difficult as the effect of cerebral palsy differs between individuals depending on the type, severity and topographical distribution (Blair and Watson, 2006, Chin et al., 2005, Himmelmann et al., 2006). Assessing muscle tone to characterise motor impairment allows identification of the types of cerebral palsy, which are 1) Hypertonia, 2) Ataxia and 3) Hypotonia. Hypertonia, or an increase in muscle tone, is the most prevelant. The three subtypes of hypertonia are spasticity, dyskinesia or mixed tone. Spasticity is the most common abnormal muscle tone (Gage et al., 2004, Stanley et al., 2000). The widely accepted definition of spasticity by Lance (1980; cited in (Gage et al., 2004, Barnes and Johnson, 2001) states:

> *"Spasticity is a motor disorder characterised by a velocity-dependant increase in tonic stretch reflexes, with exaggerated tendon jerks resulting from hyperexcitability of the stretch reflex, as one component of the upper motoneuron syndrome".*

Three subtypes of spasticity are defined, based on the regions of the body that are affected. Hemiplegia involves one sagittal half of the body with the upper limb usually more involved than the lower limb (Gage et al., 2004). Diplegia involves both sides of the body, with the legs being more involved (Gage et al., 2004). Quadriplegia involves both sides of the body and is a more severe level of diplegia, with greater involvement of the upper limbs (Gage et al., 2004). Dyskinesia presents as abnormal motor movements coinciding with voluntary movement (Gage et al., 2004) and mixed tone is a combination of spasticity and dyskinesia. Ataxic muscle tone results from injury to the cerebellum producing involuntary movements and hypotonia is decreased muscle tone (Gage et al., 2004). Figure 2.1 summarises the classification described above.

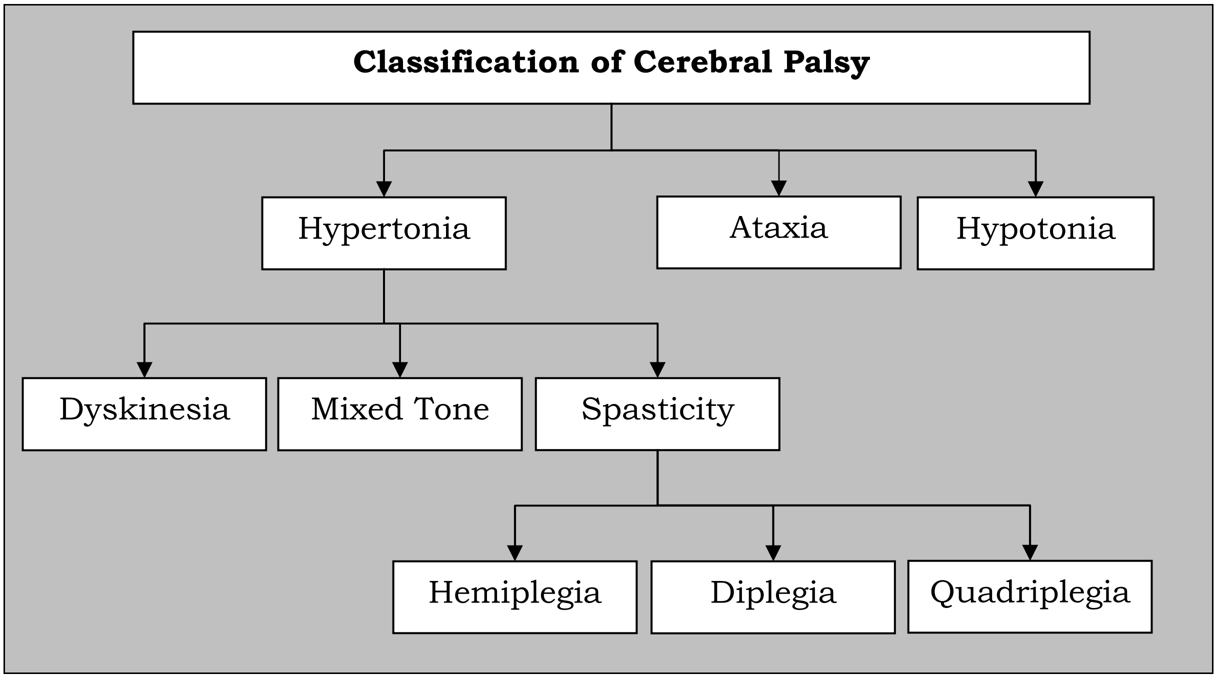

Figure 2.1 Structure of the Classification of Cerebral Palsy.

Cerebral palsy has been identified as the most common cause of early childhood disability (Carnahan et al., 2007). Epidemiological studies are sparse and methods of classification have varied. Howard et al. (2005) used the Victorian Cerebral Palsy Register to report the motor type, topographical distribution and gross motor function of the cohort of children diagnosed with cerebral palsy, born between 1990 and 1992 in Victoria, Australia. The authors found that 86% of the group had spastic type cerebral palsy (divided into subgroups of hemiplegia (30%), diplegia (24%) and quadriplegia (32%)). Dyskinesia, mixed type, ataxia and hypotonia were less common (1.5%, 6.5%, 2.8% & 2.8% respectively).

2.1.3 Classification and Qualitative Assessment Tools

Howard et al. (2005) investigated the level of severity of cerebral palsy using the Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997) which has been widely accepted (Rosenbaum et al., 2007) and is described as an important tool for description of motor function in children with cerebral palsy (Carnahan et al., 2007). This graded system was developed by Palisano and others (1997) to guide classification of severity based on function during walking and sitting (Palisano et al., 1997). Palisano and colleagues (1997) described in detail the components of each level of the GMFCS, its application to age and distinctions between levels. Table 2.1 summarises the five levels of the GMFCS and indicates the proportion of the cohort studied by Howard et al. (2005) that is classified within each level.

Similar incidence rates to Howard and others (2005) were reported in a Swedish study which also recruited the study cohort from a population-based register. Himmelmann and colleagues (2006) reported the proportion of severity levels in 411 children with cerebral palsy using the GMFCS and Bimanual Fine Motor Function (BFMF) classification scale (Table 2.2). The Bimanual Fine Motor Function scale was developed by Beckung and colleagues (2002) to classify fine motor skills and showed a strong correlation with the GMFCS (Beckung and Hagberg, 2002).

Table 2.1 Gross Motor Function Classification System outline (Palisano et al., 1997) and percentage of children born with cerebral palsy in Victoria, Australia between 1990 to 1992 (n=323, Howard et al., 2005).

GROSS MOTOR FUNCTION CLASSIFICATION SYSTEM GENERAL HEADINGS FOR EACH LEVEL		%
LEVEL I	- Walks without Limitations	35.3
LEVEL II	- Walks with Limitations	16.4
LEVEL III	- Walks Using a Hand-Held Mobility Device	14.2
LEVEL IV	- Self-Mobility with Limitations; May Use Powered Mobility	16.1
LEVEL V	- Transported in a Manual Wheelchair	18.0

Approximately 60% of the cerebral palsy child population were classified as type I or II using both systems. This indicates that they mobilise without the use of aids for short distances (Palisano et al., 1997); and can handle most objects with some quality or speed of movement limitations (Eliasson et al., 2006).

Table 2.2 Data from Himmelmann et al., 2006 showing the distribution of severity levels in gross motor function (GMFCS) and bimanual fine motor function (BFMF) within a group of children with cerebral palsy (n=411).

Level	GMFCS (%)	BFMF (%)
I	32	30.7
II	29	31.6
III	8	12.2
IV	15	11.9
V	16	13.6

The GMFCS focuses on lower limb function and does not assess or classify hand function or upper limb ability. The House classification system (House et al., 1981) is routinely used by orthopaedic surgeons to assess the outcome of surgery on thumb-in-palm and upper limb deformities in children with cerebral palsy (Van Heest, 2003). This nine level system which classes the functional ability of the hand is recommended for use to record baseline and outcome measures before and after interventions (Chin et al., 2005). Other upper limb qualitative measures have also been recommended to further document baseline and outcome measures, such as the Quality of Upper Extremity Skills Test (QUEST) and the Melbourne Unilateral Upper Limb Assessment (Melbourne Assessment) (Chin et al., 2005). More recently, the Manual Ability Classification Scale (MACS) was developed to allow classification of upper limb function in children with cerebral palsy (Eliasson et al., 2006). The MACS allows classification of bimanual function of the upper limbs during everyday tasks. There are five levels, as with the GMFCS and both scales rate level one as the greatest function and level five as the least.

Current reported outcomes for upper limb surgical treatment in cerebral palsy can improve limb posture, but often do not translate to functional gains (Van Heest et al., 2008). Van Heest and others (2008) reported that functional gains were not found after upper limb tendon transfer surgery in children with hemiplegic cerebral palsy. Their methods included the use of electromyography for quantitative measures; and movement was assessed qualitatively using two perpendicular angle video observations which allowed application of the Shriners Hospital for Children Upper Extremity Evaluation tool (SHUEE) (Davids et al., 2006). These findings are in agreement with a review of the literature reporting a lack of functional gains after upper limb surgery in cerebral palsy by van Munster et al. (2007). Due to the limited evidence regarding hand function before and after upper limb tendon transfer surgery (seven papers in total), van Muster et al. (2007) stated that it remains unclear whether functional gains are achieved with upper limb tendon transfers in children with cerebral palsy. Current qualitative methods of assessing upper limb function and the effects of treatments in patients with pathology affecting movement may not be sensitive enough to changes or improvements with treatment over time (Ramos et al., 1997).

Although qualitative measurement tools are routinely used currently in clinical practice, they rely on the clinician's subjective assessment of upper limb quality of movement (Mackey et al., 2005). There is a lack of reliable, quantitative outcome measures for the upper limbs to help guide treatment planning for children with cerebral palsy (Mackey et al., 2005).

2.2 Limitations of Previously Studied Quantitative Upper Limb Measurements

There have been various methods employed to measure upper limb motion quantitatively. Goniometers are used routinely in clinical practice, but cannot measure joint angles dynamically. Electrogoniometry has been used to measure joint angles dynamically (Barker et al., 1996), but there is a concern that the apparatus interferes with the movement being measured, introducing measurement error (Buckley, 1996).

Different variables obtained by motion analysis have been used to describe healthy and pathological upper limb movement in children. Menegoni et al. (2006) investigated the trajectory and velocity of hand movements in healthy children and children with cerebral palsy and reported deviation of the children with cerebral palsy from the healthy group. Measures of hand and joint movement smoothness during reaching tasks have previously been used to describe motor learning and development (Berthier and Keen, 2006, Chang et al., 2005, Schneider and Zernicke, 1989). Outcome measures including hand curves, velocity curves, accelerations and decelerations (Flash and Hogan, 1985) and jerk scores (Goldvasser et al., 2001, Schneider and Zernicke, 1989, Yan et al., 2000) have been used to describe the motions of normal and pathological upper limb movement. Chang et al. (2005) demonstrated a correlation between movement time and both number of movement units and normalised jerk scores (both measures of movement smoothness), during high accuracy reaching in children. While the above studies have investigated the biomechanics of upper limb movement, there has not been widespread uptake of these techniques for clinical use. This may be related to difficulty of interpretation of highly technical terms that do not translate well into practical interpretation of movement and what hinders it.

An electromagnetic sensor system was devised by Spyers-Ashby et al. (1999) to quantify hand tremors in three dimensions and O'Suilleabain et al. (2001) conducted validation studies on this system. Methodological constraints of the electromagnetic sensor system include the need to test where there are no large metal objects in the vicinity and having to avoid significant electromagnetic noise. The system requires that the sensors are quite close to the transmitter to maximise accuracy (a distance of 75cm maximum is recommended). It is understood that while this set up may be suitable for small range movements such as a tremor in the local segment measured, at present it does not accommodate measurement of multiple segments simultaneously during dynamic movement.

A system using rotary optical sensors to measure linear displacements was developed by Crosbie and Eisenhuth (1993) and further developed by Rowe et al. (1999), where 6 degrees of freedom where measured during human movement. This system involved attaching inelastic string to an anatomical landmark to measure linear displacement of the landmark in 1, 2 or 3 dimensions. The authors detailed the limitations that must be considered when implementing this measurement device. There appear to be benefits of this concept due to its portability, ease of use for the clinician and relative expense compared to a motion analysis system. However, one of the main limitations is that in three dimensional measurement of movement, the strings connected to the optical sensors in each plane cannot cross, which excludes the measurement of some rotational movements. This limitation restricts the type of movements that are able to be assessed with this system. There have been large gains of knowledge in the understanding of upper limb function in the body of research outlined above; however there has not been a widespread translation of three dimensional upper limb movement measurements from the research realm to clinical use.

2.2.1 Three Dimensional Motion Analysis of Human Movement

Upper limb motion occurs in three dimensions and therefore where possible should be measured in three dimensions. Rau et al. (2000) stated that two-dimensional measurement of upper limb motion is inappropriate, as three-dimensional measurement is necessary to adequately describe the rotational movements at the shoulder joint. With knowledge of the anatomical capabilities of each joint, joint motion can be described mathematically. The input of kinematic segment position data can then provide information of joint angles using motion analysis software. This process is known as kinematic modelling using motion analysis and will be referred to as three dimensional motion analysis.

Three dimensional motion analysis allows measurement of multiple joint angles simultaneously during dynamic movement. This method gives information about joint postures throughout movement, in three planes, with no inhibition of the pattern of movement. Assessment of upper limb dynamic movement using three dimensional motion analysis is not currently part of clinical practice. In 1992 when the QUEST was published the authors noted that computer based tracking (as in motion analysis) was expensive and not readily available, but acknowledged that preliminary motion analysis research at the time had demonstrated good sensitivity for measuring upper limb coordination (DeMatteo et al., 1993). Rau et al. (2000) stated that upper limb movement measurement was in it's infancy in comparison to lower limb movement measurement. The technology of motion analysis has advanced and the number of motion analysis laboratories around the world has steadily grown with the increased use of kinematic data obtained from clinical gait analysis.

Gait analysis is the measurement the functional task of walking using three dimensional motion analysis, which has been researched extensively, through the inquisitiveness of great minds about human locomotion (Baker, 2007). Gait has been the task used for dynamic measurement in the normal population to further understand the dynamics of the lower limbs (Rau, 2000). Through the knowledge gained over years of investigation of walking, three dimensional gait analysis has evolved into a widely used and extremely useful clinical tool in movement assessment and treatment prescription, particularly in special populations with movement disorders (Rau, 2000).

Using motion analysis technology, gait patterns within the neurotypically developed population have been found to be reliable (Kadaba et al., 1990). Steinwender et al. (2000) investigated the repeatability of three dimensional kinematic, kinetic and temporo-spatial parameters during gait in healthy children and children with cerebral palsy (Steinwender et al., 2000). Twenty children with spastic diplegia who ambulated independently (GMFCS levels I and II) and 20 children with no history of musculoskeletal problems were included in their study. Within-subject repeatability was assessed using kinematic data captured during multiple trials and on three different days within a one week period. Kinematic time series graphs of the entire movement (waveforms) were analysed using the adjusted coefficient of multiple correlations statistic (CMC) (Kadaba et al., 1989). As the r-value approaches 1 repeatability increases. Steinwender and colleagues (2000) reported waveforms being highly repeatable in the sagittal plane for the hip, knee and ankle for both groups, for within- and between-day repeated measures ($r \geq 0.83$). Healthy group frontal and transverse plane waveforms were less repeatable than sagittal plane kinematics (not including the pelvis) however the frontal and transverse planes showed good repeatability both within- and between-testing sessions ($r \geq 0.73$). In the cerebral palsy group, the frontal and transverse planes had good repeatability for within-day testing ($r \geq 0.74$). These findings demonstrated good repeatability of lower limbs kinematics within an individual with cerebral palsy (who ambulates without assistive aids).

Biomechanical analysis of gait has served as a valuable quantitative baseline and outcome measure for pre and post intervention investigations; and has contributed substantially to knowledge of normal and pathological gait patterns (Graham and Selber, 2003). Kinematic data obtained by three dimensional motion analysis is necessary to correctly identify gait patterns that are not able to be appreciated visually, due to the complex nature of gait and only being able to observe two planes at any one time (Rodda and Graham, 2001). Based on kinematic data, Rodda et al. (2001) further developed previous gait pattern classifications to define types of spastic diplegic and hemiplegic gait patterns. Kinematic criteria were used to categorise four gait patterns in spastic hemiplegia: drop foot (type I), true equinus (type II), jump knee (type III) or jump knee with hip internal rotation (type IV). Also using kinematic criteria, the authors suggested that spastic diplegic children have either a true equinus, jump knee, apparent equinus or crouch gait pattern. Kinematic data assists clinicians to differentiate between apparent equinus and true equinus gait patterns. Apparent equinus gait pattern includes normal dorsiflexion range at the ankle in stance phase, whereas a true equinus pattern will show the ankle in persistant plantarflexion throughout stance. Visual observation of this discrete difference can be difficult due to the common traits of excessive hip and knee flexion, but drastically changes the appropriate treatment course (Rodda and Graham, 2001). With implementation of three dimensional motion analysis for the clinical assessment of upper limb function, identification of kinematic movement patterns in the upper limbs has the potential to facilitate treatment of children with movement disorders in the same way that gait analysis has for the lower limbs.

2.2.2 Clinical Use of Three Dimensional Motion Analysis for Lower Limbs

Functional outcomes of lower limb treatment have improved greatly through the use of gait analysis (Rodda et al., 2006). Advances in knowledge gained in classifying gait patterns through instrumented gait analysis has allowed greater understanding of the outcomes of surgical procedures on cerebral palsy patients. Rodda et al. (2006) demonstrated functional improvements (at multiple joints in the lower limb) at one and five years after surgical correction of severe crouch gait in 10 children. Knee and ankle sagittal plane kinematics were significantly improved (towards normal) at the one year post operative assessment. Maximum knee extension in stance was 44° pre-operatively and was improved to 13° one year post-operatively (normal = 5°). Furthermore, maximum ankle dorsiflexion in stance was 29° pre-operatively and improved to 17° one year post-operatively (normal = 15°). These improvements measured at the first follow up assessment were largely maintained at five years.

Three dimensional motion analysis allows the interaction of motion in the three planes to be interpreted together. As a result, three dimensional gait analysis has allowed identification of compensatory movements that improve or disappear with appropriate treatment. When pathology interrupts a person's ability to ambulate optimally, compensations are made to achieve the goal of forward progression and alternative movement strategies are utilised (Rau, 2000). An example of this is in type IV hemiplegia with an abnormal internally rotated femur. Dobson and others (2005) reported that the compensation of abnormal pelvic rotation during gait is improved with correction of the rotational deformity in the femur. This emphasised the point that single muscle or single joint investigations are insufficient to understand and treat multi-joint movement and function (Flash and Hogan, 1985).

2.3 Three Dimensional Motion Analysis of Upper Limbs

Comparison of biomechanically typical and pathological gait using three dimensional motion analysis has enabled clinicians to improve outcomes for patients with movement disorders (Rodda and Graham, 2001). The successful use of motion analysis for the lower limbs to measure dynamic function and assess treatment outcomes has begun to translated to use in the upper limbs. As with gait analysis, recent research involving measurement of upper limb motion has moved towards three dimensional motion analysis, to provide researchers with improved understanding of upper limb movement (Rau, 2000). Upper limb movement measurement is complex due to the degrees of freedom available in upper limb joints (Schmidt, 1999, Veeger, 2003, Rau, 2000), so that the principles of clinical gait analysis are not directly adaptable (Rau, 2000). The primary issue has been mathematical description of the shoulder joint, as the large ROM that the shoulder moves through creates computational problems of angle definitions that are not encountered when describing lower limb joint motions.

2.3.1 Kinematic Modelling

Early work to identify the challenges of measuring upper limb motion using three dimensional motion analysis was conducted by Veeger and others (1997). The authors conducted cadaveric studies to investigate parameters for upper limb modelling. This work employed calculation methods from Van der Helm and colleagues (1992) to determine rotation centres and axes of the limbs. The authors stated that the glenohumeral joint could be defined at the location of the functional joint centre (measured during passive movement), with three degrees of freedom and the centre of rotation in the geometric glenohumeral joint centre. Veeger et al. (1997) reported that the elbow flexion-extension axis passed through the humeral capitulum and trochlea and that the pro-supination axis ran through the radial head and the distal ulna. Following on from this work, several groups created kinematic models to describe upper limb movement (Safaee-Rad et al., 1990a, Rab, 2002, Veeger et al., 1997, Schmidt et al., 1998, Wu et al., 2005).

Nearly 20 years ago, Safaee-Rad and colleagues (1990a) constructed one of the earliest three dimensional measuring systems using two video cameras, seven reflective markers, a calibration frame, computer-based image processing and two video recorders. Euler angle methods were used in the biomechanical model to define joint motions, based on the assumption that the segments were rigid and rotated about a fixed axis. This early methodology and model by Safaee-Rad and others (1990a) was used to measure and describe upper limb motion during performance of feeding activities in a normal population (Safaee-Rad, 1990b). The kinematic data obtained using this method demonstrated the functional ranges of motion at multiple joints simultaneously. Three dimensional motion analysis equipment and biomechanical models are now commercially available.

2.3.2 Clinical Use

Rau and colleagues (2000) suggested that upper limb three dimensional motion analysis would have a greater use in clinical settings in the future. After almost a decade, it seems there a need for international agreement on methodology and clinical implementation of three dimensional motion analysis for the upper limb. To facilitate clinical uptake of three dimensional motion analysis for upper limbs, a method of assessing upper limb kinematics was established by Rab et al. (2002). The authors presented a marker-based three dimensional measurement technique and biomechanical model, based on the principles of lower limb gait analysis. The method and model was found to be repeatable. The authors stated that their upper limb model conventions were similar to that of Veeger et al. (1997), one of few groups who had previously investigated appropriate methods for upper limb kinematic modelling. Limitations of shoulder movement description and skin movement relative to bony landmarks were identified by the authors. Rab and colleagues (2002) concluded that if these limitations are taken into careful consideration then meaningful kinematic data of upper limb movement can be produced for practical use.

Willliams and colleagues (2006) suggested that three dimensional motion analysis of upper limb movement would provide clinically relevant information about joint coordination and mobility in patients with joint disorders. The authors defined a shoulder joint marker placement protocol, joint coordinate system and definition of joint centres of the shoulder and sternoclavicular joint. This was incorporated with an upper limb model developed by Schmidt et al. (1996, 1998, 1999). This combined model was used to measure upper limb movement of a normal adult male population, as well as a group of patients with a shoulder disorder that affected shoulder movement and function (Williams et al., 2006). Differences in movement patterns were highlighted when the kinematic waveforms of a patient with a movement disorder were plotted against the mean and standard deviation wave forms of the normal population.

The interest of the above mentioned authors in three dimensional upper limb kinematics prompted the International Society of Biomechanics (ISB) to form a subcommittee, the Standardisation and Terminology Committee, to define and publish recommendations on the standardisation of methods and terminology of techniques used, to make comparisons of findings between different research groups possible (Wu et al., 2005). For use in the clinical setting, factors such as time to execute the test, reliability, accessibility (Rau, 2000), cost, expertise required by clinicians (and many more) will determine whether or not upper limb motion analyses are a viable addition to routine clinical practice.

2.4 Normative Kinematic Data of Upper Limb Movement using Three Dimensional Motion Analysis

To understand movement limitations associated with pathology, healthy movement must first be understood. It is important to have age-specific normative kinematic data available for comparison to pathological movement. Petuskey et al. (2007) reported upper limb joint angles at the point where the hand was on top of the head in healthy children, as did McIntosh and others (2002) in healthy adults using the University of New South Wales (UNSW) upper limb kinematic model. Excellent agreement between populations was found for elbow flexion posture when the hand was at the top of the head (110±7° healthy children, 109±14° adults) with greater forearm supination in healthy children compared to adults (43±16° and 32±12° respectively) at the same point during task execution. Petuskey et al. (2007) reported that separating a large age range of healthy children into groups is required due to differences found in movement strategies related to age. The difference in forearm rotation between the children and adults in these two studies highlights that the forearm rotation measure is different relative to age, however elbow flexion posture when the hand is on top of the head was not different between populations. This emphasizes the need to use child norms with small age ranges (specific to the population of interest) for use in clinical settings to compare to child groups with movement disorders rather than adult kinematic data.

Rab et al. (2002) reported upper extremity kinematic data while healthy children raised their hand to touch their head and then returned their hand to their side. For shoulder flexion, shoulder abduction, shoulder external rotation and elbow flexion, Rab et al. (2002) stated that the maximum standard deviation of the kinematic time-normalised waveforms was 25° (n=96 limbs) and suggested that this value of deviation was small enough to demonstrate measurement method reproducibility and movement execution uniformity among the subjects measured. Williams and colleagues (2006) suggested that movement patterns that were more than one standard deviation away from the mean of normative movement patterns may be defined as pathological movement patterns. Additional studies that report the variability found in non-pathological movement will add to knowledge of upper limb movement repeatability and therefore allow agreement on acceptable variability of measurement using three dimensional motion analysis.

There is a paucity of knowledge on normal ranges of motion of upper limb joint using three dimensional motion analysis. The documentation of the ranges of motion during single joint movement and functional movements in healthy children would add to current knowledge about the capabilities of upper limb movement for comparison to pathological movement.

2.4.1 Repeatability of Measurements

Results of repeatability studies of upper limb movements using three dimensional motion analysis provide evidence of both the movement repeatability and the reliability of the measurement system. In a review of previously published literature, Buckley et al. (1996) compared studies that measured biomechanical parameters during activities in daily living. The authors reported similar findings in two papers previously published by one research group, Safaee-Rad and others (1990b) and Cooper and others (1993) and concluded that results can be repeatable using three dimensional motion analysis. Further, the differences found in kinematic parameters between papers in the review article of Buckley et al. (1996) that were from varying research groups could be attributed to two main reasons. These were the orientation of hand held objects used in the movements studied and the arbitrary zero in the angle definitions of different models (Buckley, 1996). Uniformity of methods of these two factors among studies is therefore required to allow direct comparison between studies and attribute any differences found to the movements studied and not the differing methods used between research groups.

2.5 Three Dimensional Motion Analysis of Upper Limbs in Cerebral Palsy

There are few studies on three dimensional measurement of upper limb motion in healthy children, or in children with cerebral palsy. Studies of upper limb movement during functional tasks have described pathological movements compared to movements of healthy children (Mackey et al., 2006, Fitoussi et al., 2006); and investigated inter-trial repeatability of movements within individuals (Fitoussi et al., 2006); grouping of dominant and non-dominant data (Gunal et al., 1996, Mackey et al., 2006) and grouping of subjects by age (Petuskey et al., 2007) to further knowledge about pathological movement in children.

2.5.1 Joint Range of Motion

Upper limb motion analysis results in people with cerebral palsy, compared to normative kinematic data, has identified pathological movement. The hemiplegic group of children investigated by Mackey and others (2006) demonstrated increased trunk flexion and reduced forearm pro/supination range of motion (ROM) during the hand to head task compared to the controls. The hand to mouth task showed increased trunk and shoulder flexion and decreased pro/supination ROM in the group with movement disordersvcompared to the healthy group. The authors concluded that three dimensional motion analysis of upper limbs could measure differences in ROM between the affected and unaffected limbs. Mackey et al. (2006) also identified compensatory movements of increased shoulder flexion and trunk flexion related to forearm pro/supination range restriction in the hemiplegic children measured.

2.5.2 Repeatability

A dynamic upper limb task for assessment during three dimensional motion analysis needs to be repeatable to enable comparison to pathological movement and should not be assumed. Fitoussi et al. (2006) measured the kinematics of two functional movements in one healthy subject to determine intersessional repeatability. The authors also measured fifteen children with hemiplegic cerebral palsy (discussed later). While seated, two different tasks were performed. The first, named the Cookie test, involved moving an object to the mouth, as in eating/drinking, (similar to Rau et al., 2000 and Mackey et al., 2005). The second was moving an object from one place on the table surface to another, named the Displacement test. Movement patterns of the affected limb were compared to the non-affected side. The authors investigated intersession reproducibility by measuring a single healthy subject's dominant limb in four separate marker placement and static capture sessions. The authors found that the single subject movement waveforms were reproducible over the four sessions for both movements (r > 0.84), with the exception of shoulder rotation in the Cookie test, r = 0.82) and the wrist radio-ulnar deviation for the Cookie test ($r = 0.68$) and the Displacement test ($r = 0.78$). Unfortunately, the authors did not specify the age of this healthy individual. Further research is needed to consolidate these intersession results (Fitoussi et al., 2006). Within subject repeatability in a healthy child population also needs to be investigated before it is compared to pathological movements. If variability is present in the healthy population then the definition of movement disorders of the upper limbs becomes difficult, as does decisions regarding treatment and outcomes.

Preliminary investigation of the repeatability of movements within subjects has been performed by few authors. Mackey and others (2005) published kinematic data from the second and third repeats of functional movements while ignoring the first, as did Fitoussi et al. (2006). These authors did not report their reasons for ignoring the first repeat of the movement captured. Petuskey et al. (2007) only measured one repeat of the functional tasks measured in their normal subjects and therefore could not make comment on trial-to-trial repeatability. Barker et al. (1996) reported that subjects demonstrated different movement patterns for the first repetition of the movement, compared to the subsequent four repeats of the movement studied using an electrogoniometer. Familiarisation of movement wearing the apparatus may have been a factor contributing to this finding. Further investigation using repeated trials of functional movements may give insight into repeatability, learning affects and fatigue regarding the order of movements to be studied. Repeatability of movements and methodology must be established before comparison to pathological movement is suitable.

Fitoussi et al. (2006) investigated within subject reproducibility of repeats performed by each subject with cerebral palsy performing the cookie and displacement tests described above. The authors investigated the repeatability of five phases of the Cookie test and found that when the movements were separated into five phases, the reproducibility of the first phase was not as good as the other subsequent phases during the task. Identification of key events during functional upper limb tasks allows the movement to be segmented into phases; ideally meaningful to the execution of the movement, which can allow a more detailed investigation of the repeatability of each phase of movement.

2.5.3 Dominant versus Non-Dominant Limbs

Previous investigations of between-limb differences during upper limb movements have suggested significant differences between dominant and non-dominant limbs. Gunal (1996) showed between-limb differences in upper limb motion in adults, with the dominant limb demonstrating reduced ROM compared to the non-dominant limb using goniometry.

Petuskey et al. (2007) used three dimensional motion analysis techniques to measure healthy children performing functional upper limb movements to provide a normative kinematic database for comparison to pathological movement. Fifty-one healthy children aged 5-18 years were recruited for the study and both limbs were measured. They used the upper limb model described by Rab et al. (2002) to investigate five simulated ADL movements: 1) Back - hand to ipsilateral back pocket; 2) Head - hand to top of head; 3) High - high reach above head; 4) Receive - reach forward to receive change; and 5) Wave - wave with arm by side and shoulder externally rotated. Joint angles were described at a significant event during the movement, called the point of task achievement. At this event there were significant differences relative to limb dominance at the joint positions for two of the five movements measured (back and head movements). Significant differences found between the dominant and non-dominant limbs at the point of task achievement were small (less than 6°) and the authors decided to group the dominant and non-dominant kinematic data for subsequent analyses.

Mackey et al. (2006) measured 10 healthy children and 10 hemiplegic children performing the hand to head task, described by Mackey et al. (2005). Furthermore, a hand to mouth task with an object and a reaching task was also studied. Mean minimum and maximum upper limb joint angles of three repeats for each task were used for analysis. The dominant and non-dominant ROM during all tasks in the healthy subjects showed no statistical differences. The authors also found no statistical differences between the dominant limb in the healthy subjects and the unaffected limb in the subjects with pathology for all movements measured.

2.6 Summary

Upper limb impairments, such as in cerebral palsy, can affect a person's function and independence. Clinicians and researchers have used various tools to assess upper limb function and rely on these measures to classify function and measure treatment outcomes. Quantitative assessment of upper limb treatment outcomes with reliable and valid methods is required in clinical practice to inform, quantify and enhance treatment outcomes for people with movement disorders.

Three dimensional motion analysis techniques allow quantitative description of movement patterns of joints and segments during a given task. Three dimensional motion analysis of the lower limbs has been established as a reliable and valid technique which has increased knowledge of normal and pathological lower limb movement and has impacted positively on clinical practice (Rau, 2000). For example, the classification of gait patterns based on kinematics has enabled identification of movement types, which have directed treatment regimes for patients. Further investigation of upper limb movement in normal and clinical populations may assist in identifying mechanisms of movement impairment and guide treatment to maximise function for people with upper limb movement disorders. The identification of repeatable dynamic movements for analysis of the upper limbs and information about whether movements differ between dominant and non-dominant limbs are necessary to permit use of three dimensional motion analysis clinically to achieve these goals.

CHAPTER THREE

METHODOLOGY

3.1 ETHICS AND SUBJECT RECRUITMENT

Ethical approval was obtained from the University of New South Wales (UNSW) Human Research Ethics Advisory Panel (project reference number 8/04/01, see Appendix B) to conduct the outlined research at the university. Approval was also obtained from the Catholic Education Office, Sydney, to approach local schools to recruit volunteers (see Appendix C). Principals of local catholic schools were contacted (Appendix D) and asked if they would allow the circulation of the approved advertisement flyers in school documents (Appendix E). Parents of interested volunteers placed contact details on the advertisement flyer, and returned them to their school office. These flyers were then collected from the schools and the parents were contacted to arrange times that suited them for testing. At the testing session, parents were supplied with participant information statements and consequently provided signed informed consent on behalf of their child prior to participation in the study (see Appendix F,G,H).

3.2 SUBJECTS

Twenty one children between the ages of 7 and 12 participated in the project. One child had difficulty paying attention, and was noted as executing the requested movements poorly. It was decided that if data obtained from this subject was a statistical outlier, it would be excluded from the study. As this was the case, this particular child's data was not used in the analyses. This left data from 20 subjects with a mean age of 10.2 years ± 1.1 (range = 8.4-12.0). The group consisted of 10 girls and 10 boys. Within the group there were five left-handed children. Table 3.1 details relevant anthropometric information about the group of subjects included in the analysis.

Table 3.1 Anthropometric Measurements of Subjects

Anthropometric Measure	Mean (SD)	Maximum	Minimum	Number
Age (years)	10.2 (1.1)	12.0	8.4	20
Height (cm)	142.0 (9.4)	161.0	128.7	20
Weight (kg)	35.6 (8.3)	55.1	22.8	20

3.3 TESTING PROCEDURES

Testing was completed at the UNSW Biomechanics and Gait Laboratory. Experimental measures were undertaken to describe the joint range of motion (ROM) during anatomical and functional movements in healthy children using three dimensional motion analysis. Each of the eight anatomical movements were single joint movements designed to demonstrate the full ROM available at each joint of the upper limb. The two functional movements (*hand to mouth* and *hand over head*) were measured to describe the excursion of motion at different upper limb joints during typical daily activities. Movement descriptions are provided in more detail in Chapters 4 and 5. The capture sessions took approximately two hours for each participant.

3.4 MOTION ANALYSIS EQUIPMENT

An eight infra-red camera 3D motion analysis system (Vicon 612 Motion Capture System, M2 cameras with Workstation 5.2.9 software; Oxford Metrics, Oxford UK) was used to capture kinematic data at 100Hz. Twenty four retro-reflective markers of 15mm diameter were positioned on the thorax and upper limbs. The eight cameras were positioned around the laboratory to capture the movements of the subjects by ensuring that at least two cameras were able to view each marker at all times and prevent marker drop-out during trials.

3.4.1 Marker Placement

Marker positions were similar to those previously described by Meskers et al. (1998) and recommended by Anglin and Wyss (2000) in a review of upper limb motion analyses. Twenty four markers in total were used to define the trunk, clavicles, upper limb segments and upper limb joint centres (Figure 3.1). The four trunk segment markers were located on the spinous processes of C7 and T8, the jugular notch and the ziphersternal junction. Markers on the clavicle were located on each superior aspect of the acromio-clavicular joints and on the midpoint of the clavicles. For arm segment description, markers were located on the medial and lateral epicondyles in the coronal plane of the humerus, near the deltoid insertion, on the styloid processes of the radius and ulna and also on the metcarpo-phalangeal joint of the third digit (dorsal surface) bilaterally. During the static capture, markers were placed anterior and posterior to the perceived functional glenohumeral joint centre bilaterally to define the glenohumeral joint centres. The anterior and posterior glenohumeral joint

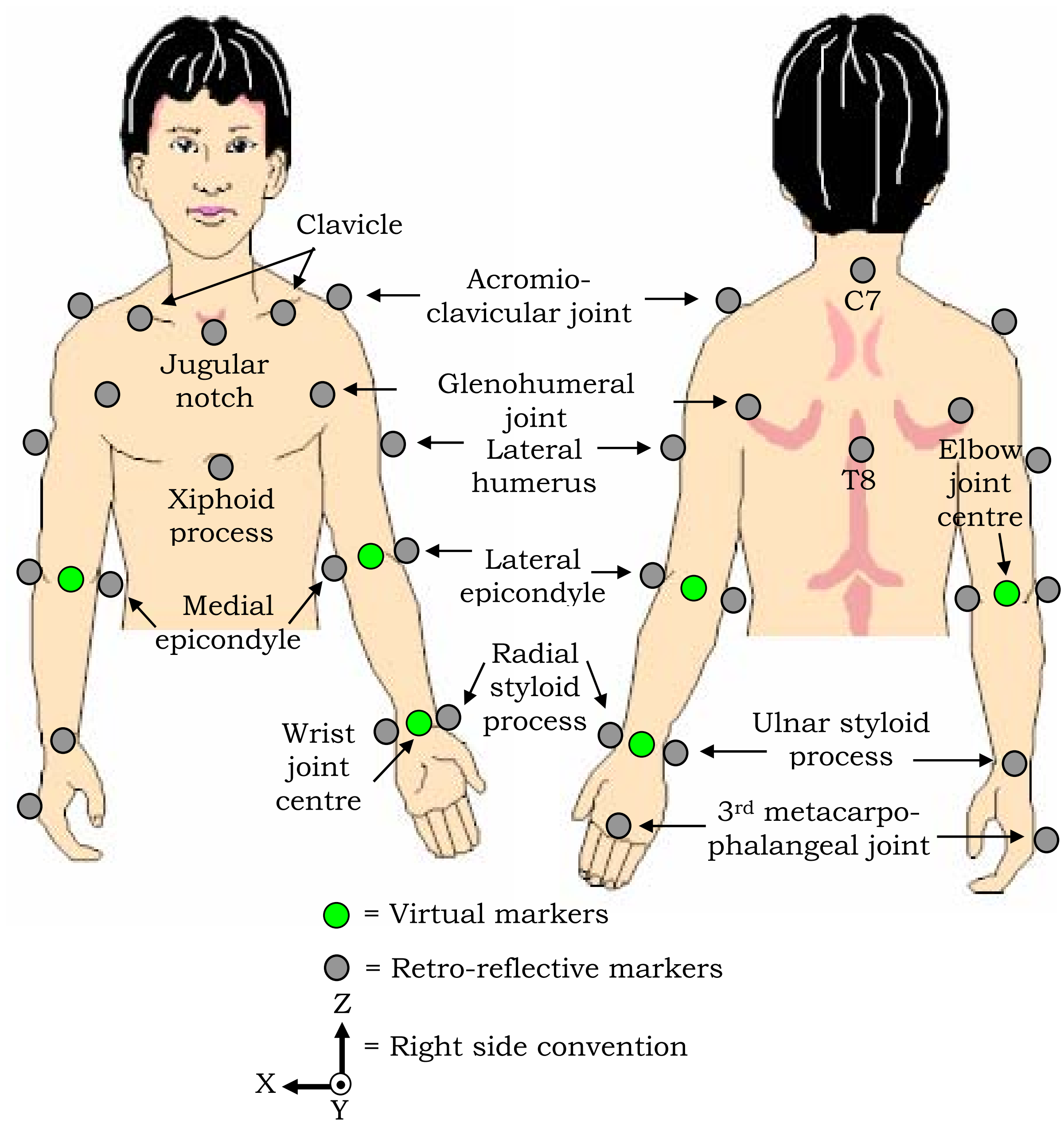

Figure 3.1 Anterior and posterior view of marker position configuration. Drawing adapted from SmartDraw (Version 2009.54, San Diego USA).

markers had the potential to obstruct movement, therefore they were removed for dynamic testing. The position of the glenohumeral joints were measured in the biomechanical model relative to the ipsilateral clavicle segment (defined by the ipsilateral acromio-clavicular joint and jugular notch markers) in the static trial and used to create virtual markers for the dynamic trials (refer to Appendix J for model definitions).

3.4.2 Static Capture

A static capture trial of the marker placement was first performed to associate the technical axes (arrangement of markers on the skin) with the anatomical axes (embedded axes referring to bony orientations) (Cappozzo, 1991). This is known as the anatomical axis calibration (Cappozzo, 1984). Previous work using the UNSW upper limb kinematic model to measure upper limb movement in children with hemiplegic cerebral palsy was conducted to investigate the effects of botulinum toxin treatment (Dwan et al., 2002). Large differences between maximum joint angles were found in forearm pronation and supination. The ROM also showed large standard deviations for both the affected and unaffected limbs (55±48° of the unaffected limb). The factors proposed to contribute to this result were a small sample size (n=8) of children with varying impairments and treatment; poor execution of the movement (not being repeated the same by the children due to attentional demands) and differences in marker placement standardisation between subjects (Dwan et al., 2002). To address the issue of marker placement standardisation between subjects, a rig was made to place the subject into pre-determined joint angles for the static capture for improved positioning of the joints in the known joint angles for all subjects; and for improved anatomical axis calibration.

3.4.2.1 Static Position Pilot Testing

Exploratory testing of upper limb position in the static rig was carried out, in order to position the upper limbs in predetermined angles, also orientating the humerus away from the trunk and avoid gimbal lock measurement error during the static capture. Gimbal lock is an indeterminable angle using Euler angle calculation. When a longitudinal axis of a segment is parallel to an axis of the reference joint co-ordinate axis, the rotation of that segment about the reference axis is indeterminable (Rab, 2002). In the UNSW upper limb kinematic model rotation sequence, gimbal lock occurs when the humerus Z axis is at 0° and 180° (humerus vertical, either near arm by side or straight upwards). Different static positions were tested in one adult volunteer to identify the best static position to use to avoid gimbal lock during the static capture.

During this piloting test, the marker placement was constant for all measures. Dynamic trials were performed by the adult volunteer and were processed using the different static trials to determine the optimum static position to be used during the testing phase of the project. A static rig was subsequently constructed to support the subjects in the optimum static position identified.

The static position chosen was humerus elevated (abducted) 60° in neutral shoulder rotation and horizontal flexion. The elbow was flexed at 90° with the forearm in neutral pronation/supination position. The wrist flexion was not fixed. This was determined by the thickness of the forearm segment, as the palmar surface of the hand was placed flat on the arm support board bilaterally. Therefore, the wrist flexion joint angle was not adjusted in the static trials. Radio-ulnar deviation position was neutral.

3.4.2.2 Design of the Static Rig

Arm supports were made of light wood and held in place by a freestanding vertical metal frame (one each side). The arm supports were secured at 60° to the vertical (Figure 3.2B). As the heights of the vertical frames were fixed, wooden steps of varying heights were used so that the apexes of the vertical frames and arm supports fitted into each subjects axilla, so as not to cause any shoulder girdle elevation. This ensured that the subject's humerus was resting comfortably on the arm supports at 60˚ of elevation.

The distance between the two vertical frames of the rig was adjustable to suit different subjects' trunk widths. Pheasant (2002) was consulted to find the required range of trunk widths needed to accommodate all possible subject sizes.

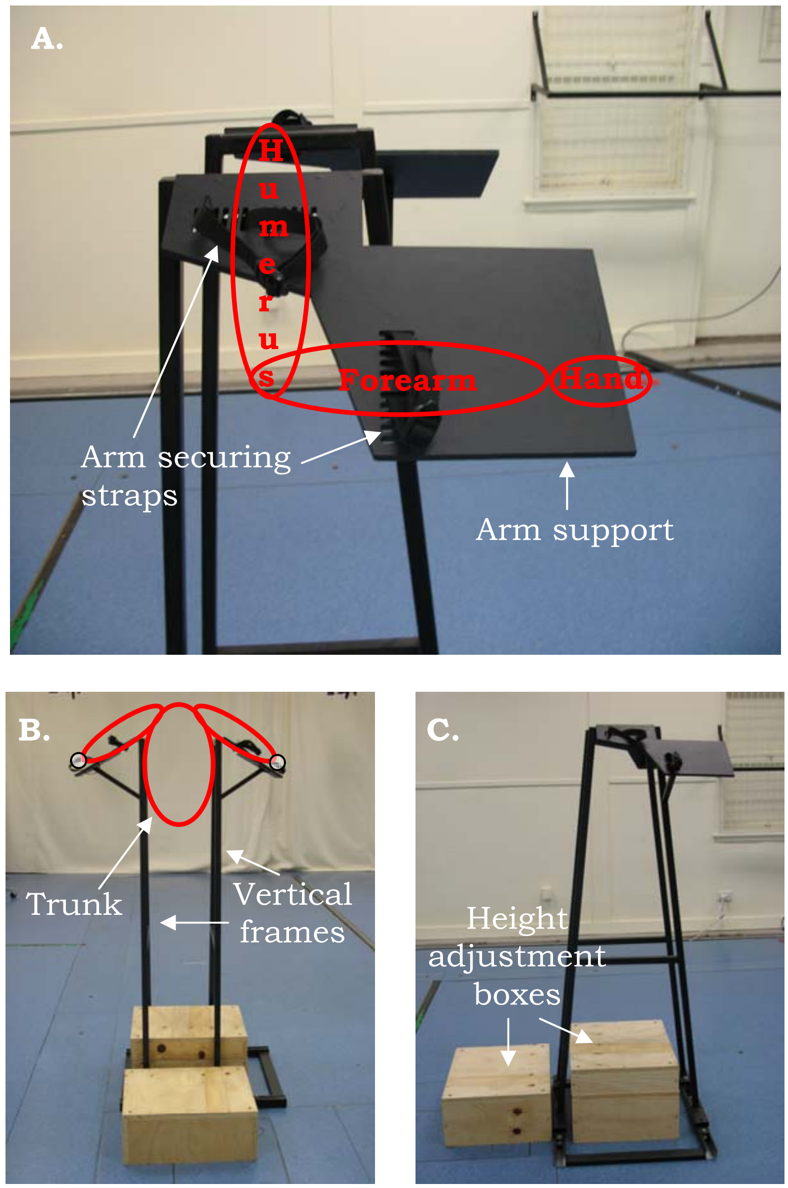

Figure 3.2 A) Arm supports of the static rig; B) posterior view; and C) sagittal view of static rig.

Once the subjects were at the correct standing height they were instructed to stand upright to align the trunk sagittal, coronal and transverse planes with the global coordinate system. The arms were placed flat on the arm support boards and secured with straps (Figure 3.2A), placing the arms into the known joint angles. The children were asked to stand very still and a static capture was taken. The static capture was processed while the subjects remained in the rig, to ensure that the shoulder joint rotation angle measured was not affected by gimbal lock. The static capture was repeated if necessary until the effects of gimbal lock were not present (shoulder joint rotation angle measured accurately).

Standardising the joint angle positions of the upper limb and trunk using the fixed structure also allowed adjustment of the measured upper limb joint angle positions to coincide with the known joint angle positions in the static capture. During the data processing phase, the measured joint angles during the static capture were adjusted if necessary to describe the joint angles that the arms were placed in with the use of the static rig.

3.5 KINEMATIC MODEL

The UNSW upper limb kinematic model was used (McIntosh et al., 2002). The UNSW upper limb kinematic model is a rigid body model that defines the segments of the thorax and bilateral clavicles, upper arms, forearms and hands.

3.5.1 Location of Joint Centres

There is a paucity of published data on the location of joint centres in children and reference has been made to adult measurements to estimate the joint centres for modelling (Rab, 2002, Veeger et al., 1997). The UNSW upper limb kinematic model uses the linear regression equation method to locate joint centres of the trunk, shoulder, elbow and wrist. This method was one of the two recommended for joint centre location in the most recent recommendations of the International Society of Biomechanics (Wu et al., 2005). The UNSW model assumes that the joint centres of rotation are fixed and that there is no translation at the joints. (McIntosh et al., 2002).

3.5.2 Coordinate Axes Definitions

Local coordinate axis definitions are outlined in Table 3.2. The humerus movement is described relative to the thorax rather than attempting to describe scapulohumeral movement, as this is particularly difficult (Rab, 2002).

Table 3.2 Local Coordinate Axis Definitions (for right side of the body). ^{G} denotes global coordinates of the marker referenced. Reproduced from McIntosh et al. (2002).

Trunk	^Gz_t:	$\{(^GJUGN + {}^GC7)/2 - (^GXIPH + {}^GT8)/2\} / \lVert(^GJUGN + {}^GC7)/2 - (^GXIPH + {}^GT8)/2\rVert$
	^Gx_t:	$(^GJUGN - {}^GC7)/\lVert {}^GJUGN - {}^GC7\rVert \times {}^Gz_t$
	^Gy_t:	$^Gz_t \times {}^Gx_t$
	Origin:	^GJUGN
Clavicle	^Gx_c:	$(^GACJ - {}^GJUGN)/\lVert {}^GACJ - {}^GJUGN\rVert$
	^Gy_c:	$^Gz_t \times {}^Gx_c$ (NB: Trunk z-axis)
	^Gz_c:	$^Gx_c \times {}^Gy_c$
	Origin:	^GJUGN
Upper Arm	^Gz_u:	$(^GGHJ - {}^GEJC)/\lVert {}^GGHJ - {}^GEJC\rVert$
	^Gy_u:	$^Gz_u \times (^GLEP - {}^GMEP)/\lVert {}^GLEP - {}^GMEP\rVert$
	^Gx_u:	$^Gy_u \times {}^Gz_u$
	Origin:	^GGHJ
Forearm	*Flexion/Extension*	
	$^Gz_{f1}$:	$(^GEJC - {}^GWJC)/\lVert {}^GEJC - {}^GWJC\rVert$
	$^Gy_{f1}$:	$^Gz_{f1} \times (^GLEP - {}^GMEP)/\lVert {}^GLEP - {}^GMEP\rVert$
	$^Gx_{f1}$:	$^Gy_{f1} \times {}^Gz_{f1}$
	Origin:	^GEJC
Forearm	*Forearm Pronation/Supination*	
	$^Gz_{f2}$:	$(^GEJC - {}^GULN)/\lVert {}^GEJC - {}^GULN\rVert$
	$^Gy_{f2}$:	$^Gz_{f2} \times (^GRAD - {}^GULN)/\lVert {}^GRAD - {}^GULN\rVert$
	$^Gx_{f2}$:	$^Gy_{f2} \times {}^Gz_{f2}$
	Origin:	^GEJC
Hand	$^Gz_{f3}$:	$(^GEJC - {}^GWJC)/\lVert {}^GEJC - {}^GWJC\rVert$
	$^Gy_{f3}$:	$^Gz_{f3} \times (^GRAD - {}^GULN)/\lVert {}^GRAD - {}^GULN\rVert$
	$^Gx_{f3}$:	$^Gy_{f3} \times {}^Gz_{f3}$
	Origin:	^GEJC
	Wrist	
	^Gz_h:	$(^GWJC - {}^GMCP)/\lVert {}^GWJC - {}^GMCP\rVert$
	^Gy_h:	$^Gz_h \times (^GRAD - {}^GULN)/\lVert {}^GRAD - {}^GULN\rVert$
	^Gx_h:	$^Gy_h \times {}^Gz_h$
	Origin:	^GWJC

3.5.3 Order of Rotations

Notation of rotation about axes is done with the three axes written in order and a "´" and "´´" placed after the second and third axes of rotation. X-Y´-Z´´ (rotation about three axes) was used as recommended by Rab and others (2002) and by the International Society of Biomechanics (Wu et al., 2005) for its suitability to clinical applications. Z-Y´-Z´´ rotation sequence was chosen for the UNSW upper limb kinematic model as it was previously found that rotation about two axes better suits the upper limb due to the large ranges of motion of the shoulder (McIntosh et al., 2002). Both methods have limitations regarding calculation issues with Euler angles (gimbal lock).

The Z-Y´-Z´´ order of rotation is used in the UNSW upper limb kinematic model to describe humerus position relative to the trunk. The first rotation occurs about the longitudinal axis of the humerus and orientates the humerus to the plane in which it will be elevated. The second rotation occurs in the coronal plane of the humerus, abducting the humerus to the selected angle of elevation. The third rotation occurs about the longitudinal axis of the humerus again to select the desired final position of the humerus (Rab, 2002).

Table 3.3 Joint Rotation Definitions. Reproduced from McIntosh et al. (2002).

Joint	Rotation Sequence	Joint Angle
Shoulder	Z Y′ Z″	Horizontal Flexion/Extension Elevation Internal/External Rotation
Elbow	X (Y′) (Z″)	Flexion/Extension
Forearm (2nd forearm segment)	Z (X′) (Y″)	Pronation/Supination
Wrist	X Y′ (Z″)	Flexion/Extension Radio/Ulnar Deviation

3.5.4 Output Angle Conventions

The anatomical position was defined as the zero positions of the shoulder, elbow and wrist joints. For forearm pronation and supination, the zero position was defined as the mid-position of forearm pronation and supination rather than the anatomical position (which is supinated). Shoulder horizontal flexion is positive when the humerus is in front of the coronal plane of the trunk; and negative when the humerus is behind the coronal plane of the trunk. Shoulder elevation angles increases positively with increasing elevation away from the anatomical position. Shoulder internal rotation is positive; shoulder external rotation is negative. Elbow flexion is positive; and any elbow hyperextension is represented with a negative value. At the forearm, pronation is positive and supination is negative. Wrist flexion is positive and wrist extension is negative. Radial deviation is positive and ulnar deviation is negative.

3.6 DATA TREATMENT

The data were initially processed using Vicon Workstation software version 5.2.9 (Oxford Metrics, Oxford UK) to generate three dimensional workspace files (C3D data files). Marker trajectories were labelled to identify each marker with reference to its anatomical location.

The three dimensional workspace files were then opened in Vicon Bodybuilder software version 3.6 (Oxford Metrics, Oxford UK). The data were visually inspected in the three dimensional workspace and inspected graphically in the three planes (Figure 3.3) to manually fill any small gaps in the data (a maximum of approximately ten frames). The interpolation routine was a cubic spline.

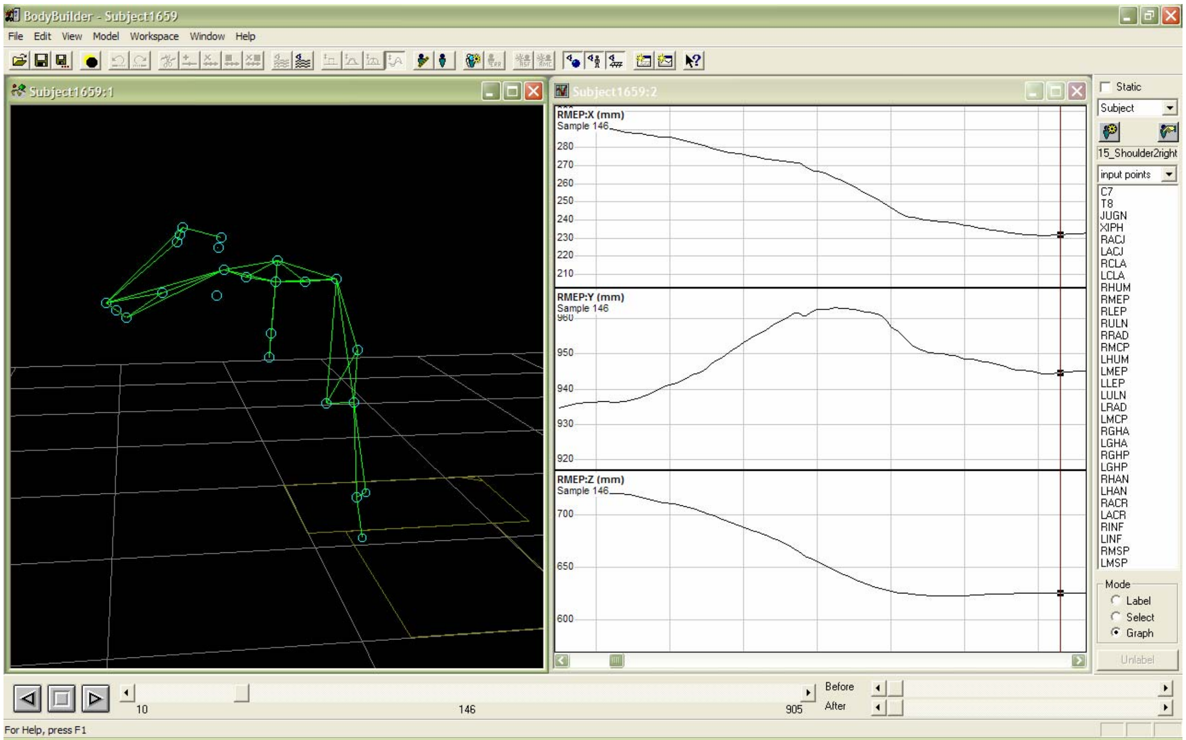

Figure 3.3 Three dimensional workspace file (left) and graphed trajectory of a marker (right) during an elbow flexion movement. Vicon Bodybuilder software version 3.6.

The data were then filtered in the Vicon Bodybuilder program using the three point weighted average filter. The option of removing spikes from the data with a threshold factor of two was also used. The UNSW upper limb kinematic model was applied to the data. Text files were output, containing time-series data in three planes of the trunk segment angles (measured with respect to the global axes) and forearm and hand segment angles (relative to the proximal segments). Trunk and humerus position data were also exported, as the humerus rotation was calculated in the next step.

The text files exported from Vicon Bodybuilder were further processed using Matlab software version 6.5 (The MathWorks Inc, Natick Massachusetts, USA). A Matlab model (see Appendix I, J & K) used the position data of the humerus and trunk to calculate shoulder joint data in three planes using Euler angles with the rotation sequences described previously (Table 3.3) and graphed all data for visual inspection. A graphical user interface and code were developed in Matlab to allow batch processing of the data files, graph the data, identify each maximum and minimum from each trial (Patton and Dwan, 2007). The peak joint angle data for all subjects were exported in one file for each movement performed (described in Chapters 4 and 5).

3.7 STATISTICAL ANALYSIS

Data were analysed using SPSS 15.0 for Windows (SPSS Inc, Chicago, USA). A 2-factor analysis of variance was performed on variables of interest, to determine differences between dominant/non-dominant limbs and repeatability between multiple trials. Post-hoc analyses were conducted using the Scheffe test to identify where significant differences existed between repeated trials. Level of significance was set at $p<0.05$.

The repeatability analysis within SPSS was performed to obtain intraclass correlation coefficients (ICC) to report the strength of agreement of the repeated measures. The two-way mixed model was used in SPSS, which correlates to ICC model 3,1. A confidence interval (CI) of 95% was used. The ICC and CI are reported in results chapters (ICC = x (CI = y-z)). The strength of agreement of measures was assessed based on the guidelines reported by Landis and Koch (1977) (see Table 3.4).

Table 3.4 Guidelines for strength of agreement of data using intraclass correlation coefficients (reproduced from Landis & Koch (1977)).

Intraclass Correlation Coefficient (kappa statistic)	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost Perfect

The coefficient of multiple correlations (CMC's) method employed by Kadaba et al. (1989) was used to determine the repeatability of the waveforms (time-series data) of the time-normalised data. Calculation of the variability of data within a subject using the adjusted coefficient of multiple determination (CMD, represented as the *r*-squared value) provides an indication of the variability between each repeat movement, and is not affected by system calibration or joint angle definitions, as these are constant within each subject for the testing period (Steinwender et al., 2000). The CMD for evaluating repeatability of waveforms within a test day is determined by the equation:

$$R_a^2 = 1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \overline{Y}_{it})^2 / MT(N-1)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}(Y_{ijt} - \overline{Y}_{i})^2 / M(NT-1)}$$

where Yijt is the tth time point of the jth run on the ith test day, $\overline{Y}$it is the average at time point t on the ith test day (Kadaba et al., 1989).

Kadaba and colleagues (1989) reported that an r-squared value (CMD) tends towards 1 when the waveforms are similar, and tends towards zero when the waveforms are dissimilar. The CMC is the positive square root of the CMD. Kadaba et al. (1989) reported *r*, being the CMC, however there was no explanation of why it was chosen over r-squared. The guidelines for assessing repeatability using the CMC were not stated, and the guidelines for CMD were used to comment on the repeatability of waveforms. Other authors have used the method presented by Kadaba et al. (1989) and reported the CMC rather than the CMD (Steinwender et al., 2000, Mackey et al., 2005, Fitoussi et al., 2006). Fitoussi and others (2006) selected a scale for use with the CMC, with an $r>0.94$ denoting excellent reproducibility, $r=0.84$-0.94 representing good reproducibility, and $r<0.84$ indicating poor reproducibility. Mackey et al. (2005) reported values of $r=0.49$ and above as moderate to high; and $r=0.70$ and above as high. Steinwender and colleagues (2000) discussed CMC results comparatively (one variable more or less repeatable than the next). For this thesis, CMCs were calculated on waveforms of subjects performing functional upper limb tasks (Chapter 5) with the findings discussed comparatively between joints and also in comparison to previous research. The CMC repeatability scores are directly related to the magnitude of the ROM measured, which is a limitation taken into consideration during data interpretation.

CHAPTER FOUR

JOINT RANGE OF MOTION KINEMATICS

4.1 INTRODUCTION

Understanding the range of motion (ROM) of each joint in the upper limb is fundamental to appreciate the potential for complex segment movements performed during daily activities. There is a paucity of knowledge on upper limb maximum joint angles and ROM in the healthy child population. The current study was undertaken to demonstrate the upper limb ROM capabilities of healthy children aged between 8 and 12 years. The study aims to 1) provide descriptive statistics on the upper limb maximum joint angles and joint ROM in a healthy child population; 2) examine reproducibility across repeated trials and 3) determine whether differences in upper limb joint ROM exist between dominant and non-dominant limbs of healthy children. This information will provide a normative dataset necessary to understand upper limb movement limitations in children with pathological conditions.

4.2 METHODS

Twenty healthy child volunteers were asked to perform eight different movements along anatomical planes: 1) shoulder flexion; 2) shoulder abduction; 3) shoulder internal rotation; 4) shoulder external rotation; 5) elbow flexion and extension; 6) forearm pronation and supination; 7) wrist flexion and extension; and 8) radial and ulnar deviation. These movements, collectively referred to as anatomical movements, were devised to demonstrate maximum joint angles of upper limb joints in the degrees of freedom available at each joint.

Each anatomical movement was described and demonstrated to each subject, who then practiced the movement approximately three times with each limb before data collection with the motion capture system described in Chapter 3. Six successful repeats of each movement were performed with both the dominant and non-dominant limbs (performed separately with the order randomised). Subjects moved at a self selected pace during movements and all were performed in a standing position. Capture trials where the performance of the movements did not appear to elicit maximum joint angles (via real time visual inspection) were excluded, and the capture trial was repeated. Selection of trials to be excluded and therefore performed again was a subjective assessment, at times when the subject was either not concentrating or appeared to execute the movement poorly. The limb was returned to the start position after achieving the maximum joint angles described in all movements.

Shoulder joint maximum elevation angle was measured during two of the anatomical movements; 1) shoulder joint flexion and 2) shoulder joint abduction movements (Figure 4.1 A and B respectively). Two movements were chosen to measure elevation angle because the way the arm is moved to demonstrate the elevation angle is not unique. The plane of elevation can vary (e.g. arm in front of the trunk, to the side or behind the trunk). Both movements of shoulder joint forward flexion and shoulder joint abduction were performed to capture shoulder joint maximum elevation angle to determine whether the means by which this joint position was achieved affected the measured maximum angle. For these two movements, subjects started with their hand resting comfortably by their side. The start position was the shoulder joint minimum elevation angle, which is near the region of gimbal lock. As this angle is susceptible to measurement error related to the limitations of the model and is not an angle of clinical interest, this measure was not reported. Therefore, shoulder joint elevation ROM was not investigated in this study.

External shoulder joint rotation was assessed while the upper arm was maintained next to the trunk (Figure 4.2). The movement began with the upper arm by the subject's side, elbow flexed in front of the subject to the horizontal, neutral forearm pro/supination and neutral wrist position. The arm was rotated externally to measure the shoulder joint external rotation maximum angle.

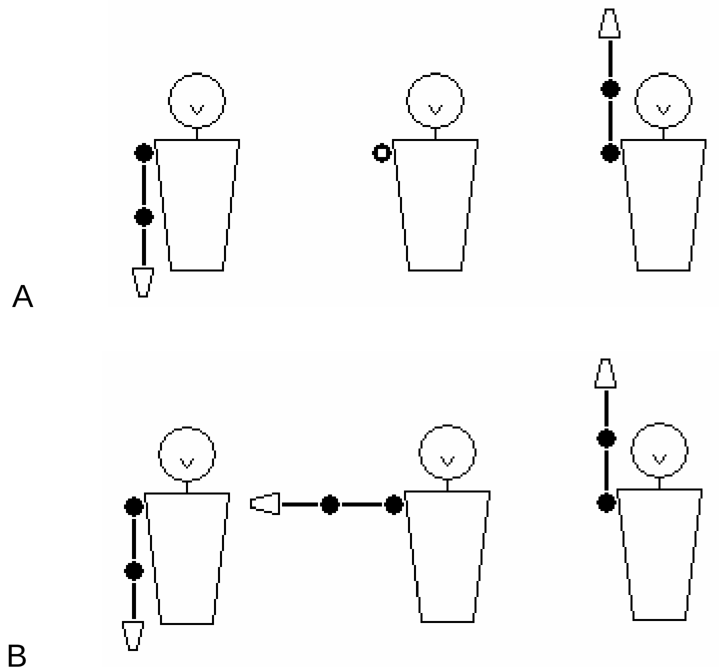

Figure 4.1 Measurement of shoulder joint elevation kinematics via shoulder flexion (A) and abduction (B) movements

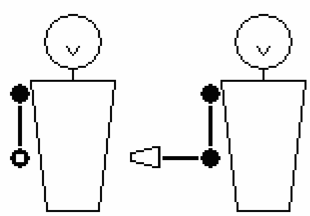

Figure 4.2 Shoulder joint external rotation movement

The maximum shoulder joint internal rotation angle was measured during a hand behind the back movement (Figure 4.3). The hand started by the subject's side and was moved up the subject's back so that the dorsal surface of the hand rested in the middle of the subject's back. The subjects were instructed to drop their elbow forward while the hand was behind the back to elicit maximum shoulder joint internal rotation.

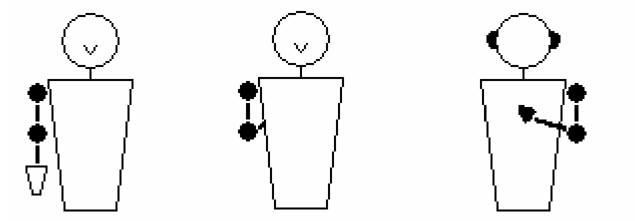

Figure 4.3 Shoulder joint internal rotation measured during the hand behind back movement

Elbow flexion and extension was measured from a starting position with the arm abducted to shoulder height in the coronal plane, the elbow extended and the palmar surface facing upwards (Figure 4.4). This was the maximum elbow extension angle. The hand was moved towards the shoulder in the coronal plane to the point of maximum elbow flexion, and then returned to the start position.

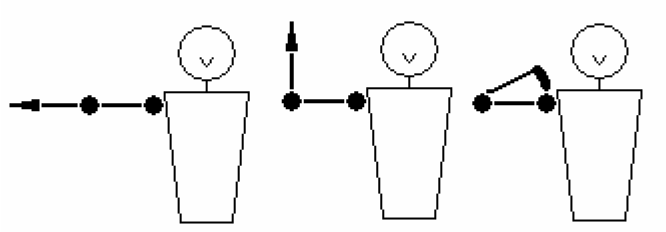

Figure 4.4 Elbow joint flexion and extension movement

Forearm pronation and supination was measured during a movement that started with the upper arm by the subject's side, the elbow flexed to horizontal in the saggital plane, the palm facing upwards and the wrist in a neutral position (Figure 4.5). The forearm was rotated in both directions to the pronation and supination maximum joint angles.

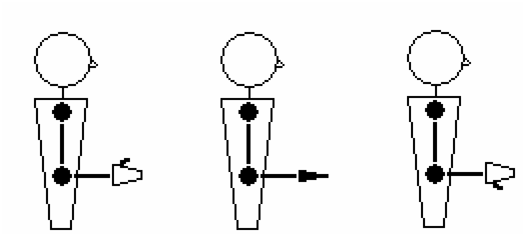

Figure 4.5 Forearm pronation and supination movement

The wrist flexion and extension movement started with the subject's upper arm flexed to horizontal in the saggital plane, elbow extended, wrist in the neutral anatomical position and the palmar surface of the hand facing downwards (Figure 4.6). The hand moved to the point of maximum wrist flexion, then to the point of maximum wrist extension.

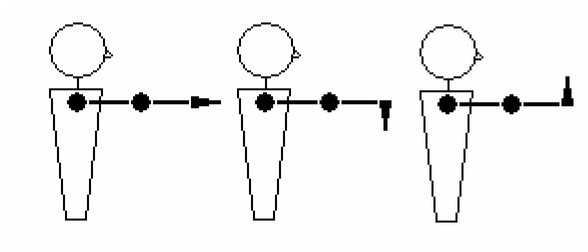

Figure 4.6 Wrist joint flexion and extension movement

Radial and ulnar deviation movement started with the subject's upper arm flexed in the sagittal plane to approximately 45° below the horizontal, elbow extended, wrist in a neutral flexion/extension position and palmar surface of the hand facing downwards (Figure 4.7). The hand moved to the point of maximum radial deviation, then to the point of maximum ulnar deviation.

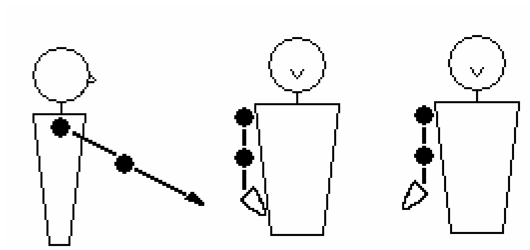

Figure 4.7 Wrist joint radial and ulnar deviation movement

4.3 Statistical Analysis

Group maximum joint angle and joint ROM variables were compiled into datasets for each joint. Data were analysed using SPSS 15.0 for Windows (SPSS Inc, Chicago, USA). A 2-factor analysis of variance was performed on each measured maximum joint angle, with limb dominance and repeated trials as factors. These tests were conducted to determine whether significant differences of the maximum joint angles existed between: 1) dominant and non-dominant limbs; 2) repeated trials; and 3) interactions between limb dominance and repeated trials. Statistical significance was set at $p < 0.05$. Post-hoc analysis using the Scheffe test was performed as necessary to identify where significant differences existed between trials and interactions. The intraclass correlation coefficient test (ICC) was also performed on the data to report the strength of agreement of the repeated trials for the group.

Joint ROM was calculated from the maximum joint angles in each direction of each plane of motion. For example, maximum elbow flexion and elbow extension were used to calculate the joint ROM in the flexion/extension plane of the elbow joint. Data presented in this way provided the range that the joints moved through irrespective of differences between absolute values of maximum joint angles between subjects. Analysis of variance tests were performed on the joint ROM data to determine whether significant differences existed between the dominant and non-dominant limbs.

4.4 RESULTS

The maximum angles for all joints of the upper limb demonstrated during the anatomical movements for healthy children are presented in Table 4.1. Data are reported for dominant and non dominant limbs. Group mean and standard deviations for maximum joint angle were calculated from 6 trials of each movement. For the hand behind back movement, two subjects did not have six complete trials of the movement due to technical errors that were not detected at the time of data capture. For the radial and ulnar deviation movement, one subject did not have six complete trials of the movement due to technical errors, also not detected at the time of capture. For these two movements, the number of subjects with complete data sets available was reduced to 18 and 19, respectively with six repeats of the movements available for analysis. Please refer to section 3.7 for description of statistical analyses.

4.4.1 Shoulder Elevation

The variable measured during the shoulder flexion and shoulder abduction movements was shoulder joint elevation, which represents the degree of humerus elevation relative to the vertical. Comparing these two movements for degree of elevation, the humerus was found to be similar, but shoulder flexion gave slightly higher shoulder elevation than the shoulder abduction movement (3°) for both the dominant and non-dominant limbs.

4.4.2 Joint ROM

Joint ROM was calculated from the maximum joint angles in each plane of motion and are presented in Table 4.1. For example, the joint ROM for forearm pronation/supination was calculated by subtracting the maximum forearm supination angle from the maximum forearm pronation angle, to give the joint ROM demonstrated in that plane. The greatest joint ROM

Table 4.1 Mean (SD) maximum joint angles for upper limb joints during anatomical movements in healthy children.

Joint Plane	Maximum Joint Angle (°)		Joint Range of Motion (°)	
	Dominant	Non-Dominant	Dominant	Non-Dominant
Shoulder Elevation Max (Shoulder Flexion)	146 (7)	147 (6)	-	-
Shoulder Elevation Max (Shoulder Abduction)	143 (6)	144 (6)	-	-
Shoulder Internal Rotation	122* (14)	124 (16)	184 (24)	185 (25)
Shoulder External Rotation	-61* (23)	-59 (23)		
Elbow Flexion	136* (6)	138 (7)	135* (7)	138 (6)
Elbow Extension	2 (8)	0 (10)		
Forearm Pronation	66* (11)	69 (10)	133* (13)	141 (12)
Forearm Supination	-67* (8)	-71 (11)		
Wrist Flexion	66* (7)	70 (6)	116 (11)	119 (10)
Wrist Extension	-49 (7)	-49 (6)		
Radial Deviation	20* (5)	23 (7)	40 (6)	41 (8)
Ulnar Deviation	-20* (6)	-18 (6)		

* = significant difference between dominant and non-dominant limbs ($p<0.05$)

demonstrated for all upper limbs was shoulder rotation (185±25°, non-dominant limb). The smallest ROM for all upper limbs was radial and ulnar deviation (40±6°, dominant limb).

4.4.3 Intra-Subject Repeatability

To investigate intra-subject repeatability, six trials of the anatomical movements from each subject were analysed for each maximum joint angle. The analysis of variance found no main effects for repeated trials for all maximum joint angles, confirming the hypothesis that upper limb maximum joint angles are similar between repeated trials during a single testing session. The strength of agreement of maximum joint angles for the group was either substantial or almost perfect for all measures of the dominant and non-dominant limbs (ICC $\geq$ 0.647) with the exception of wrist extension in the non-dominant limb which was moderate (ICC = 0.593, CI = 0.412-0.775) (see Table 4.2).

4.4.4 The Effect of Limb Dominance

Maximum joint angles were investigated for differences between the dominant and non-dominant limbs. Significant differences were found in maximum joint angles for shoulder joint internal and external rotation ($p=0.00$ for both measures), elbow flexion ($p=0.02$), forearm pronation ($p=0.01$) and supination ($p=0.00$), wrist flexion ($p=0.00$) and radial ($p=0.00$)

and ulnar deviation (p=0.03). See Appendix L for full statistical results of the 2 factor analysis of variance tests.

Table 4.2 Intraclass correlation coefficients (ICC) and confidence intervals (CI) for maximum joint angles during the anatomical movements in healthy children.

Joint Plane	Dominant		Non-Dominant	
	ICC	(CI)	ICC	(CI)
Shoulder Elevation Maximum during Shoulder Flexion	0.840	(0.731-0.992)	0.774	(0.636-0.887)
Shoulder Elevation Maximum during Shoulder Abduction	0.807	(0.683-0.905)	0.798	(0.670-0.900)
Shoulder Internal Rotation	0.819	(0.693-0.915)	0.864	(0.762-0.938)
Shoulder External Rotation	0.742	(0.593-0.868)	0.699	(0.538-0.843)
Elbow Flexion	0.955	(0.919-0.979)	0.970	(0.946-0.986)
Elbow Extension	0.873	(0.781-0.939)	0.961	(0.929-0.982)
Forearm Pronation	0.930	(0.876-0.968)	0.875	(0.786-0.941)
Forearm Supination	0.916	(0.852-0.961)	0.942	(0.896-0.973)
Wrist Flexion	0.663	(0.492-0.820)	0.682	(0.516-0.832)
Wrist Extension	0.684	(0.518-0.833)	0.593	(0.412-0.775)
Radial Deviation	0.853	(0.748-0.931)	0.927	(0.868-0.967)
Ulnar Deviation	0.842	(0.730-0.925)	0.647	(0.469-0.815)

The joint ROM measures were also tested for differences between the dominant and non-dominant limbs. Elbow flex/ext and forearm pro/supination ROM were significantly reduced in the dominant, compared to non-dominant limbs. The degree of difference for these measures was 3° and 8° less respectively.

4.5 DISCUSSION

Maximum joint angles during anatomical movements were measured in a healthy child population using three dimensional motion analysis. Quantifying the joint ROM in healthy children provides a normative database for comparison to populations and individuals with movement disorders.. This study has provided descriptive statistics for anatomical movements in healthy children, and investigated trial-to-trial reproducibility and differences between the dominant and non-dominant limbs.

4.5.1 Maximum Joint Angles

Descriptive statistics presented in Table 4.1 of maximum joint angles and joint ROM quantifies the degree of motion available in the upper limb joints of healthy children during active movements along anatomical planes.

Maximum shoulder joint elevation angle was measured in two different movements (shoulder joint flexion and shoulder joint abduction) to investigate whether the end of range shoulder joint elevation angle is influenced by the plane of movement of the upper arm. The two movements elicited comparable results of shoulder joint elevation and there was no significant difference between the dominant and non-dominant limbs. Therefore, it appears that shoulder joint maximum elevation angle measurement is consistent irrespective of the orientation of the upper arm during the movement to achieve the final joint position.

4.5.1.1 Comparison to Goniometric Measures

Joint ROM is routinely assessed in clinical practice for restriction of range. A large body of research using goniometry has provided normative bands for comparison to pathological movement. Maximum joint angles of shoulder internal rotation, forearm supination and wrist joint ulnar deviation found in the healthy child population involved in this study differed from findings previously reported in healthy adults using goniometry (Rothstein et al., 1990). Conversely, child shoulder joint external rotation, elbow joint flexion, forearm pronation and wrist joint flexion, extension and radial deviation ranges in this study were comparable to those reported by Rothstein (1990).

The meta-analysis by Rothstein (1990) reported varied results across studies. Many did not specify the study population or details of techniques used for measurement, including whether the movement was active or passive (Rothstein, 1985), which may have accounted for the large amount of variability between studies. For example, forearm pronation maximum joint angles reported ranged from 50° to 90°. Despite this large variation in reported maximum joint angles over several studies, the healthy child data reported on the current study remained outside the ranges reported for adults. Despite differences in methods of measuring joint motion, which should be taken into consideration, it seems that the maximum joint angles demonstrated by healthy children are not comparable to that of healthy adults.

Reporting of goniometric upper limb measurements in scientific publications has diminished over the last 10 to 20 years. Gunal et al. (1996) performed one of the more recent studies measuring upper limb ROM using goniometry. The authors measured active and passive upper limb joint extremes in 1000 young adult males as part of military service entry. The group was not necessarily representative of men their age (18-22 years) as they would be likely to be more active than the general population. The measures reported by Gunal et al. (1996) were in agreement with maximum joint angles reported by Rothstein (1990). The small standard deviations (less than 10°) and large subject numbers in the study by Gunal et al.(1996) suggests that these measurements are repeatable and representative of the population studied. This study provides further evidence for differences in upper limb maximum joint angles between adult and child populations, irrespective of the methods used.

The movement of placing the hand behind the back was used in the current study, in an attempt to achieve the maximum shoulder joint internal rotation angle. This movement demonstrated a significantly larger shoulder joint internal rotation maximum angle than previously reported goniometrically by Gunal and colleagues (1996) when healthy adult males performed active shoulder joint internal rotation while supine (95.5±12.6° dominant limb). The difference between the current findings and that of Gunal and colleagues (1996) may be related to the different movements used to measure shoulder joint internal rotation, the different populations studied or the different measurement methods used.

4.5.1.2 Comparison to Reported Kinematic Maximum Joint Angles

There is a paucity of upper limb kinematic joint angle measurement in healthy children. A small number of authors have reported upper limb joint angles during functional tasks in healthy children for comparison to pathological movement (Fitoussi et al., 2006, Mackey et al., 2005, Mackey et al., 2006, Petuskey et al., 2007, Rau, 2000), however no studies were found reporting joint ROM in healthy children for comparison with the dataset found in the current study.

4.5.2 Joint ROM

Few studies have measured upper limb ROM using three dimensional motion analysis techniques. McIntosh et al. (2002) reported upper limb ROM in 13 young adults with a mean age of 24 (SD 4) years,) during anatomical movements, using the UNSW upper limb model employed in the current study. With the exception of shoulder rotation ROM, joint ROM results for this adult population were comparable to those found in the current study. The methodology used for measuring shoulder rotation differed between the two studies, as McIntosh and others (2002) did not combine the hand behind back movement with the external shoulder rotation movement to describe the full range of shoulder rotation. Therefore, shoulder rotation reported by McIntosh and others (2002) is likely to be an underestimation of full shoulder rotation. The agreement between McIntosh et al.(2002) and this study, using the same model and methodology, in adult and child populations, suggests that the methods are reliable and that healthy adults and children have similar joint ranges of motion.

Another study has employed three dimensional motion analysis using the UNSW upper limb biomechanical model in children with hemiplegic cerebral palsy. Dwan and colleagues (2002) measured elbow joint flexion /extension, forearm pronation/supination and wrist joint flexion/extension ROM in 8 children with spastic hemiplegia (5-8 years) during anatomical movements. Forearm pronation/supination ROM in the unaffected limb was comparable to results in the current study. However, the elbow and wrist flexion/extension ROMs reported by Dwan et al. (2002) were less than those reported in the current study. These differences may be related to the younger age of the hemiplegic children. The learned non-use of the affected limb and the resultant increased use of the unaffected limb may also influence the muscle length (related to increased use) and therefore decrease ROM in the unaffected limb in children with spastic hemiplegic cerebral palsy. Since these studies shared a common kinematic model and movements measured, results suggest that differences in elbow and wrist flexion/extension ROM between healthy children and the unaffected limbs of children with cerebral palsy are evident.

4.5.2.1 Arc of Motion about the Anatomical Zero Joint Position

Combining the information of the maximum joint angles and the joint ROM allows the distribution of range about the anatomical zero joint position to be deciphered. Comparison of the distribution of range for each upper limb joint to that of children with movement disorders may assist to identify the origin of the limitations of movements in pathological populations. Symmetry of range about the anatomical zero position was demonstrated for forearm pronation and supination, wrist flexion and extension and wrist radial and ulnar deviation. For shoulder rotation, there was a ratio of 2:1 for internal to external rotation, respectively, about the zero position. As elbow extension is near the anatomical zero position, most of the range of elbow motion was in the flexion direction for the healthy children, therefore discussion about arc of movement symmetry about the anatomical zero position is not relevant in this case. In children with movement disorders, identifying the ratio of the two joint positions about a joint plane (for example wrist flexion and extension) and how it differs from the healthy child population can help guide treatment decision making to improve function.

4.5.3 Repeatability

It is important to compare results over repeated trials to determine whether the movements were is repeatable. No significant differences were found between movement repeats for all measures, showing that the measurements of maximum joint angles using the methods described are repeatable in healthy children within a testing session. The children were asked to move their arms to achieve the maximum joint angles. There was no statistical difference across repeats, demonstrating that the children reached similar maximum joint angles each time they repeated the movement. Intraclass correlations revealed that the strength of agreement of group maximum joint angle measurement of repeated trials was moderate or better, based on the classifications on the strength of agreement by Landis and Koch (1997). These results suggest that the movements are repeatable within a testing session for investigating joint maximum angles in this population. These findings also suggest that fewer trials are likely to be adequate to establish representative values in future testing, given that the movements were found to be repeatable.

4.5.4 Dominant and Non-Dominant Limb Differences

Maximum joint angles and joint ROM measures for the dominant and non-dominant limbs during anatomical movements were analysed to investigate whether differences existed between limbs. Significant differences existed between the dominant and non-dominant limb in 8 of the 12 maximum joint angles measured. For shoulder rotation, there was an internal rotation bias in the non-dominant limb joint ROM relative to the dominant limb. For wrist deviation, a radial deviation bias existed in the non-dominant limb joint ROM compared to the dominant limb. This translated to no significant differences in joint ROM between dominant and non-dominant limbs for these joint degrees of freedom, however the arc of movement that the joints had available was different as measured by the maximum joint angles. Elbow flexion, forearm pronation and supination were significantly less in the dominant limb, which translated to significantly smaller joint ROM in the dominant limb. Therefore differences exist between the dominant and non-dominant limbs when measuring joint kinematics.

The magnitude of the significant differences found between the dominant and non-dominant limb kinematics may not be clinically significant. The significant differences found in maximum joint angles between the dominant and non-dominant limbs were 4° or less in all cases. There were also significant differences between the dominant and non-dominant limbs in 2 of the 5 joint ROM measures. These differences were 8° or less in all cases. Gunal et al. (1996) found that the dominant limb had significantly lower ROM in 13 out of the 18 upper limb active and passive ROM reported using goniometry, in a population of 1000 healthy adult males. Most of the differences were also 4° or less. Gunal and others (1996) suggested that that the significantly smaller degrees of motion demonstrated by the dominant limb compared to the non-dominant limb may be related to mild degenerative changes and ligament damage related to the increased use compared to the non-dominant side. However differences between limbs do not appear to increase with age as the findings of the current study show that the absolute differences found in healthy children are comparable.

The differences found between joint motions of the dominant and non-dominant limbs may be due to greater use of the dominant limb in daily living. Musculotendonous unit length shortens over time with repetitive use (Herring et al., 1984). Musculotendonous units of the dominant limb are exposed to greater use due to limb dominance, which may therefore cause a decrease in joint ROM based on the adaptation of the musculotendonous units due to the increased use of the dominant limb relative to the non-dominant limb. Therefore the differences between limbs may be related to decreased muscle length with increased use of the dominant limb compared to the non-dominant limb.

Petuskey and colleagues (2007) investigated three dimensional motion analysis on upper limb movement in healthy children and identified differences between the dominant and non dominant limb. The authors decided to combine the dominant and non-dominant limb data based on the differences in measures being 6° or less. The decision to combine the data was argued to be due to the small absolute difference between the measures, regardless of the presence of statistical significance. Despite this, the dominant and non-dominant data were not combined in the current study as the statistically significant differences found between limbs in a healthy child dataset may have clinical relevance when comparing to populations with movement disorders.

4.6 Conclusions

This chapter provides descriptive statistics of upper limb maximum joint angles and joint ROM during anatomical movements designed to demonstrate the full ROM available in each plane of motion in healthy children. The anatomical movements and methodology employed were found to be repeatable in this group. It was also determined that there are some small but significant differences between the dominant and non-dominant limb maximum joint angles and ROM kinematics. These results provide a normative database of child upper limb joint ROM to which individuals and pathological movement may be compared.

CHAPTER FIVE

FUNCTIONAL MOVEMENT JOINT KINEMATICS

5.1 INTRODUCTION

The investigation of upper limb motion during the execution of functional movements may be the most useful way to gain information on how upper limb movement impairments impact on people's daily lives. Quantitative measurement of upper limb functional movements in healthy populations will enable further developments of rehabilitation movement training techniques, treatment prescription and assistive devices to maximise the function of people whose upper limb movement is compromised.

This study measured the upper limb peak joint angles demonstrated during two functional movements in healthy children. These peak angles, as well as their timing were also investigated for repeatability and to examine differences between the dominant and non-dominant limbs. Normative waveforms of the two functional movements in healthy children were produced for use as a reference for populations with movement disorders.

5.2 METHODS

Motion analysis equipment and marker placement, as described in Chapter 3, were employed in this study. Two functional movements that mimic activities of daily living were performed by the subjects. These movements were termed:

I. Hand to mouth
II. Hand over head

Both movements started and finished with the hand resting by the subjects' side. The hand to mouth movement was designed to mimic feeding, yawning, or other activities involving the hand touching the face. Subjects were instructed to touch the palmar surface of their fingers to their mouth (Figure 5.1). This movement is similar to the "Cookie test" reported by other authors (Fitoussi et al., 2006, Mackey et al., 2005, Mackey et al., 2006, Rau, 2000).

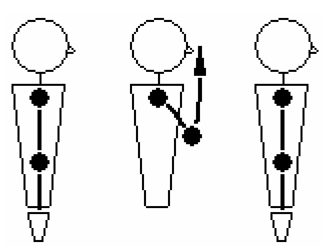

Figure 5.1 Hand to mouth movement from start to finish (sagittal view).

The hand over head movement was designed to mimic a self-grooming motion, such as brushing hair. The start position was with the subject's arm by their side. Subjects were instructed to move their hand to the forehead, run the palmar surface of their hand over the top and back of their head, and then return their hand to their side (Figure 5.2).

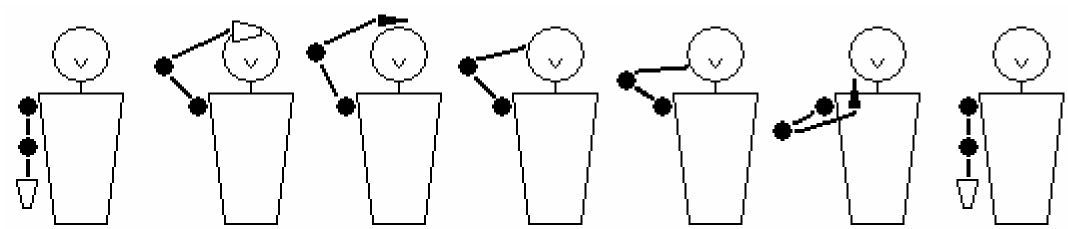

Figure 5.2 Hand over head movement from start to finish (coronal view).

Both movements were executed while the subjects were standing. Each movement was demonstrated to the subject first, and the subject then practiced the movement to demonstrate that they had interpreted all instructions correctly. The movements were executed at a self selected pace. Some subjects demonstrated poor execution of the movements at times, where they did not pass the hand over the top of the head. Verbal instruction was given at these times to correct the subject's execution by instructing them to ensure that their hand passed over the top of their head. The movements were repeated by the subjects until three successful performances on subject's dominant and non-dominant limbs were captured for analysis.

5.2.1 Data Treatment

The movement onset and finish of each repeat was identified visually in the Vicon Workstation software by identifying when the stick figure appeared to either initiate movement or cease movement of the limb. Each data capture file was trimmed so that the data in each trial constituted 100% of one movement repeat. The UNSW biomechanical model was applied to the data in Vicon Bodybuilder version 3.6 (Oxford Metrics, Oxford UK) and Matlab 6.5 (The MathWorks Inc, Natick Massachusetts, USA), as described in Chapter 3. Code, written in Matlab 6.5 (Patton and Dwan, 2007) was used to output the peak joint angles and excursions of the upper limb.

It should be noted that the angles reported in this study are described as *peak* joint angles during the functional movements, as they are not necessarily the *maximum* angle available at the joint, which was reported in Chapter 4. Similarly, *joint excursion* reported in this study describes the arc that the joints moved through during the movement, which is not necessarily the *joint range of motion* available at the joints demonstrated in Chapter 4.

Data were time-normalised to allow for comparison of movement waveforms between repeats and between subjects. This involved resampling data so that all trials contained the same amount of data points. To improve the resampling of data points at the beginning and end of the trials, the value of the first and last data points were repeated before and after the original data set (Figure 5.3). This tripled the number of data points per movement repeat. Data were then resampled using the Matlab resample function. The file was then cropped to the middle third of the resampled file to generate the time-normalised data for each movement.

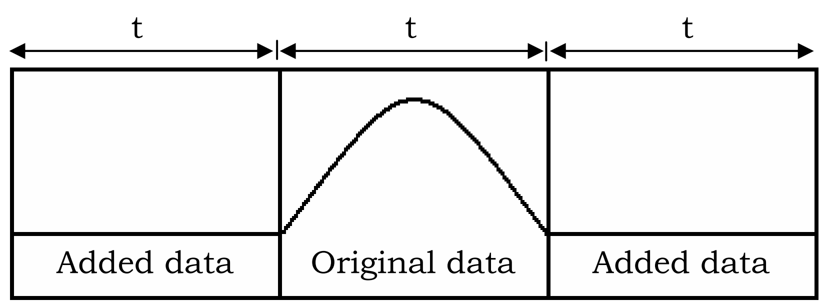

Figure 5.3 Representation of preparation of data for resampling.

The time-normalised data contained 201 samples, meaning that there were data points every 0.5% of the movement duration. Each trial from each subject was collated and group means and standard deviations for each 0.5% of the movement duration were calculated, and plotted. Graphs of the joint degrees of freedom were arranged in a single page format, to provide a normative dataset of upper limb movement.

The following variables were generated during the two functional movements for dominant and non-dominant limbs:

I. Upper limb peak joint angles.
II. Timing of upper limb peak joint angles.
III. Excursions of upper limb joints.

These variables were reported for each joint degree of freedom as means for the group.

The data were visually inspected for normal distribution. In some timing of peak joint angle data sets, very distinct bimodal distributions were observed indicating that the peak joint angles occurred at either the beginning or end of the movement. This was the case for the timing of shoulder joint horizontal extension, shoulder joint internal rotation and elbow joint extension, for both the hand to mouth and hand over head movements. These data sets were therefore excluded from the ANOVA investigation of the timing for the group.

Finally, the angular data for each joint degree of freedom was presented as waveforms of the entire movement. These data are reported separately for the hand to mouth movement and the hand over head movement.

5.2.2 Statistical Analysis

Data were analysed using SPSS 15.0 for Windows (SPSS Inc, Chicago, USA). A 2-factor analysis of variance was performed on each peak joint angle. The two factors were limb dominance and repeats. Results determined whether significant differences existed between 1) limb dominance; 2) repeated measures; and 3) interactions between limb dominance and the repeated measures. Statistical significance was set at $p < 0.05$. Post-hoc analysis using the Scheffe test was performed as necessary to identify where significant differences existed between repeats. The intraclass correlation coefficient test (ICC) was also performed on the peak joint angle kinematic data and the timing of the peak joint angle data to report the strength of agreement of the repeated trials for the group.

The Adjusted Coefficient of Multiple Correlations (CMC's) were calculated to quantify the variability of the movement waveform within and between subjects for both the hand to mouth and hand over head movements (see Chapter 3 for calculations).

5.3 Results

5.3.1 The Hand to Mouth Movement

The peak joint angles and the joint excursions of motion demonstrated during the hand to mouth movement for healthy children are presented in Table 5.1. Data are reported as group means and standard deviation across 3 repeats for dominant and non-dominant limbs.

5.3.1.1 Peak Joint Angles

The peak joint angles required to perform the hand to mouth movement in healthy children are presented in Table 5.1. During the hand to mouth movement, the upper limb demonstrated more shoulder horizontal flexion than extension, showing that the task required the humerus to be anterior to the trunk to a greater degree than a position posterior to the trunk. Shoulder joint elevation peak was 45±9° dominant limb which shows that the humerus was not elevated to the horizontal during this movement. There were similar ranges of shoulder internal and external rotation required for the hand to mouth movement. The elbow joint did move into an extension position at any point during the movement. More forearm supination than pronation was used for this movement. More wrist flexion than extension was necessary to execute the hand to mouth movement, whereas similar ranges of ulnar and radial deviation were found to be used.

Table 5.1 Mean (standard deviation) upper limb peak joint angles and excursions during the hand to mouth movement.

Joint Plane	Peak Joint Angle (°)		Joint Excursions (°)	
	Dominant	Non-Dominant	Dominant	Non-Dominant
Shoulder Joint Horizontal Flexion	88 (10)	92 (11)	125 (26)	129 (29)
Shoulder Joint Horizontal Extension	-36 (24)	-38 (27)		
Shoulder Joint Elevation Maximum	45 (9)	42 (10)	-	-
Shoulder Joint Internal Rotation	63 (26)	55 (27)	120 (26)	120 (25)
Shoulder Joint External Rotation	-57* (11)	-64 (20)		
Elbow Flexion	134 (5)	137 (8)	114 (7)	121 (8)
Elbow Extension	20* (7)	16 (9)		
Forearm Pronation	5 (20)	4 (20)	48 (16)	50 (11)
Forearm Supination	-43 (10)	-47 (12)		
Wrist Flexion	20 (11)	19 (7)	28 (7)	24 (8)
Wrist Extension	-8 (11)	-5 (8)		
Radial Deviation	11 (6)	12 (7)	21 (6)	21 (7)
Ulnar Deviation	-10 (5)	-8 (5)		

* = significant difference ($p<0.05$) between dominant and non-dominant limbs

5.3.1.2 Joint Excursions

The greatest joint excursions of motion were demonstrated in the horizontal plane of the shoulder joint (Table 5.1). Large excursions of motion were also demonstrated at the shoulder for rotation; and in elbow flexion (greater than 90°). The hand to mouth movement required smaller joint excursions about the forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation joint planes (50° or less). Compared to the joint ROM's demonstrated in Chapter 5, the hand to mouth movement elicited a small proportion of the available ROM for these distal upper limb joints.

5.3.1.3 Between-limb Differences in Peak Joint Angles

There were significant differences in the peak joint angles measured between the dominant and non-dominant limbs for shoulder external rotation and elbow extension (Table 5.1). The dominant limb demonstrated less shoulder joint external rotation than the non-dominant limb (57±11° and 64±20° respectively). Dominant limb elbow joint extension was less than the non-dominant limb (20±7° and 16±9° of elbow joint flexion respectively).

5.3.1.4 Repeatability of Peak Joint Angles

The ANOVA revealed no main effects for repeated trials. Intraclass correlations showed the strength of agreement of the peak joint angles for the group were moderate or better (ICC ≥ 0.61), with the exception of wrist extension in the non-dominant limb which was fair using the Landis and Koch (1977) classification of the statistical test results (ICC = 0.375). These results confirm the hypothesis that peak joint angles were repeatable within subjects across 3 repeats within the same testing session, with the exception of wrist extension. There were also no significant limb×repeat interaction effects for the factors of repeated trials and limb dominance.

5.3.1.5 Timing of Peak Joint Angles

Table 5.3 shows timing of the peak joint angles, presented as the percent of movement time, averaged for the group. All peak joint angles occurred in approximately the middle third of the movement, between 35-60% of the hand to mouth movement duration. The first and last thirds of the movements would generally be when the limb was either moving from or to the side of the body. Shoulder joint horizontal flexion (across the front of the trunk), elevation maximum and external rotation all occurred near the mid point of the movement duration within 6% of each other in the dominant limb. This is most likely when the hand was in contact with the

Table 5.2 Intraclass correlation coefficients (ICC) and confidence intervals (CI) for peak joint angles during the hand to mouth movement in healthy children.

Joint Plane	Dominant		Non-Dominant	
	ICC	(CI)	ICC	(CI)
Shoulder Joint Horizontal Flexion	0.871	(0.752-0.942)	0.847	(0.711-0.931)
Shoulder Joint Horizontal Extension	0.606	(0.357-0.802)	0.630	(0.388-0.816)
Shoulder Joint Elevation Maximum	0.809	(0.647-0.912)	0.831	(0.684-0.923)
Shoulder Internal Rotation	0.650	(0.415-0.828)	0.662	(0.430-0.834)
Shoulder External Rotation	0.715	(0.503-0.863)	0.814	(0.655-0.914)
Elbow Flexion	0.828	(0.679-0.922)	0.963	(0.924-0.984)
Elbow Extension	0.730	(0.526-0.871)	0.825	(0.673-0.920)
Forearm Pronation	0.696	(0.477-0.853)	0.745	(0.548-0.879)
Forearm Supination	0.588	(0.334-0.791)	0.657	(0.424-0.832)
Wrist Flexion	0.798	(0.630-0.907)	0.611	(0.363-0.805)
Wrist Extension	0.662	(0.430-0.834)	0.375	(0.099-0.649)
Radial Deviation	0.651	(0.415-0.828)	0.731	(0.527-0.872)
Ulnar Deviation	0.494	(0.223-0.732)	0.450	(0.176-0.703)

mouth. Forearm pronation was the last peak joint angle to occur during the hand to mouth movement. Wrist extension peak joint angle occurred before the wrist flexion peak and ulnar deviation peak occurred before radial deviation peak.

5.3.1.6 Between-limb Differences in Timing of Peak Joint Angles

There were no significant differences between the dominant and non-dominant limbs in the timing of the peak joint angles during the hand to mouth movement (Table 5.3).

5.3.1.7 Repeatability of Timing of Peak Joint Angles

The ANOVA revealed no significant differences between repeated trials in the timing of peak joint angles. There were no significant limb×repeat interaction effects for the timing of the peak joint angles during the hand to mouth movement. The intraclass correlation however showed that the strength of agreement for the timing of peak joint angles was poor to slight in most cases (ICC $\leq$ 0.16). The strongest relationships were shoulder horizontal flexion in the dominant limb and elbow flexion in the non-dominant limb which was moderate.

Table 5.3 Mean (standard deviation) of the relative timing of peak upper limb joint postures during the hand to mouth movement.

Joint plane	Timing of Peak Joint Angle (%)	
	Dominant	Non-Dominant
Shoulder Joint Horizontal Flexion	52 (7)	51 (4)
Shoulder Joint Horizontal Extension	44‡ (22)	56 (18)
Shoulder Joint Elevation Maximum	49 (6)	50 (7)
Shoulder Joint Internal Rotation	44 (22)	49 (21)
Shoulder Joint External Rotation	55 (14)	49 (11)
Elbow Flexion	48 (5)	47 (5)
Elbow Extension	54† (28)	54 (25)
Forearm Pronation	60 (26)	58 (22)
Forearm Supination	42 (15)	42 (13)
Wrist Flexion	55 (31)	51 (15)
Wrist Extension	47 (15)	52 (16)
Radial Deviation	52 (11)	55 (9)
Ulnar Deviation	35 (22)	48 (22)

† = significant difference ($p<0.05$) between repeats
‡ = significant interaction of factors ($p<0.05$)

5.3.1.8 Repeatability of the Waveforms

The repeatability of the waveforms of the hand to mouth movement was analysed using the Adjusted Coefficient of Multiple Correlations statistic

Table 5.4 Intraclass correlation coefficients (ICC) and confidence intervals (CI) for the timing of peak joint angles during the hand to mouth movement in healthy children.

Joint Plane	Dominant	Non-Dominant
	ICC (CI)	ICC (CI)
Shoulder Joint Horizontal Flexion	0.454(0.180-0.705)	-0.108(-0.284-0.179)
Shoulder Joint Horizontal Extension	-0.162(-0.318-0.108)	-0.292(-0.394- -0.090)
Shoulder Joint Elevation Maximum	0.168(-0.086-0.479)	0.162(-0.091-0.473)
Shoulder Internal Rotation	-0.215(-0.350-0.032)	-0.227(-0.356-0.015)
Shoulder External Rotation	0.386(0.110-0.657)	-0.149(-0.31-0.125)
Elbow Flexion	0.206(-0.055-0.513)	0.413(0.138-0.677)
Elbow Extension	0.095(-0.143-0.409)	-0.051(-0.247-0.250)
Forearm Pronation	0.053(-0.175-0.366)	-0.102(-0.281-0.187)
Forearm Supination	0.264(-0.005-0.563)	-0.079(-0.265-0.216)
Wrist Flexion	0.330(0.055-0.615)	-0.296(-0.395- -0.095)
Wrist Extension	-0.096(-0.277-0.195)	-0.026(-0.194-0.338)
Radial Deviation	0.119(-0.125-0.443)	-0.073(-0.262-0.223)
Ulnar Deviation	-0.057(-0.251-0.243)	-0.131(-0.299-0.149)

(CMC), described in Chapter 3. Group means (standard deviations) of the within-subject CMC for hand to mouth movement are presented in Table 5.5.

Repeatability of waveforms in all planes of shoulder movement and elbow flexion and extension were highly repeatable within subjects, shown by high CMC values ($r \geq 0.79$, Table 5.5). Forearm pronation and supination, and radial and ulnar deviation were moderately repeatable during the hand to mouth movement (r = 0.67-0.72). Wrist flexion and extension showed low repeatability for the hand to mouth movement, however given that the ROM at this joint is small, and the limitation of the CMC statistic is sensitive to the magnitude of the measure, the findings of the CMC for the wrist flexion/extension and radial/ulnar deviation may be underestimated. For all segments, the dominant limb was either comparable or more repeatable than the non-dominant limb.

5.3.1.9 Normative Data Waveforms

The entire dataset of three repeats for twenty subjects were averaged to give mean and standard deviation waveforms for upper limb joints for both dominant and non-dominant limbs. This data is displayed graphically (Figure 5.4) and provides normative data waveforms of the upper limbs during the hand to mouth movement in healthy children.

Table 5.5 Mean (standard deviation) within-subject Adjusted Coefficient of Multiple Correlations for upper limb motion during the hand to mouth movement.

Joint Plane	Within-Subject	
	Dominant	Non-Dominant
Shoulder Joint Horizontal Flex/Ext	0.91 (0.1)	0.86 (0.1)
Shoulder Joint Elevation	0.92 (0.1)	0.89 (0.1)
Shoulder Joint Rotation	0.88 (0.1)	0.79 (0.2)
Elbow Flex/Ext	0.97 (0.0)	0.96 (0.0)
Forearm Pro/Sup	0.67 (0.2)	0.68 (0.2)
Wrist Flex/Ext	0.56 (0.2)	0.46 (0.2)
Radial/Ulnar Dev	0.72 (0.1)	0.67 (0.2)

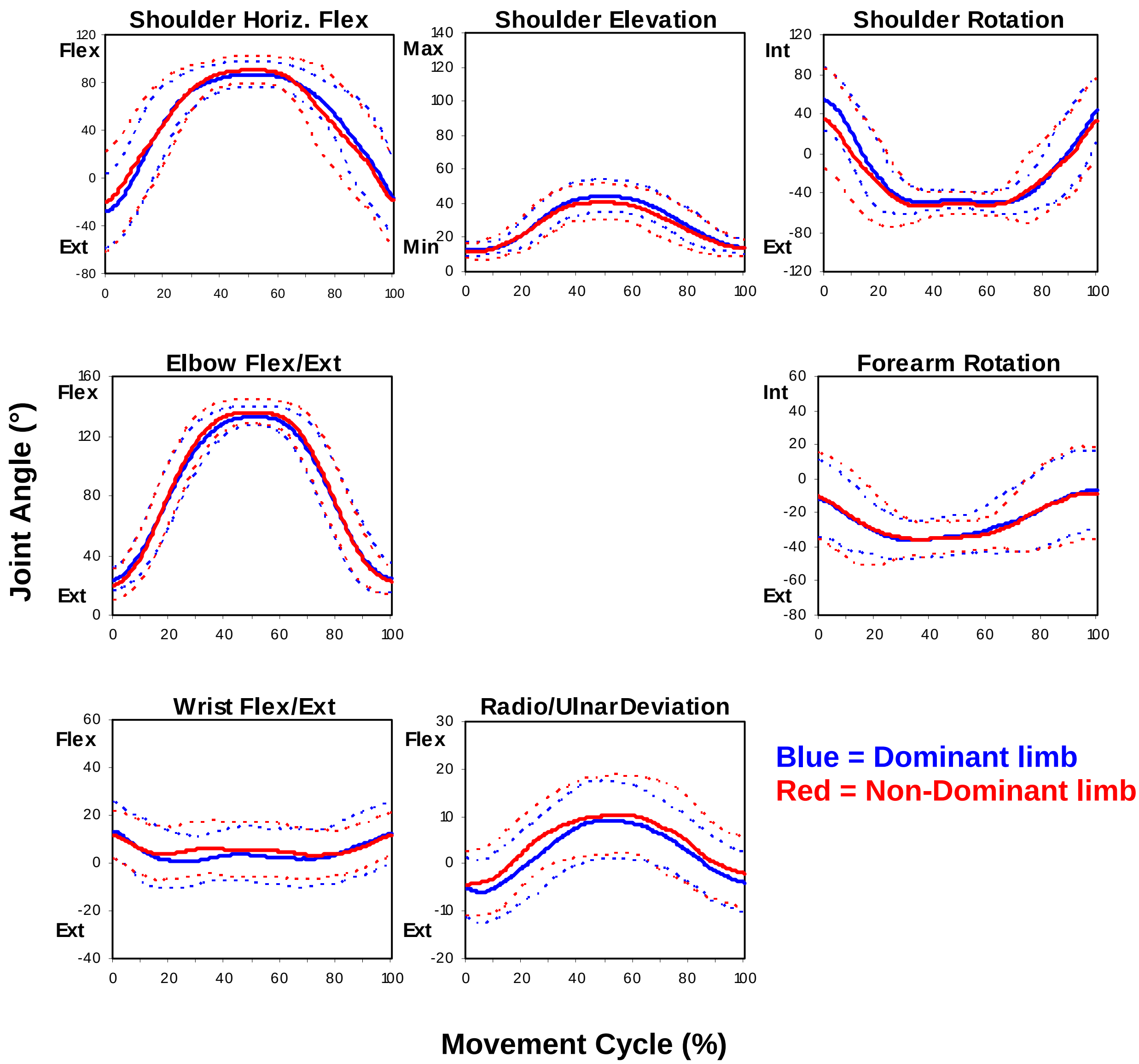

Figure 5.4 Time-normalised graphs of upper limb joints during the hand to mouth movement in healthy children. The graphs are arranged with joints represented in rows and planes of movement arranged in columns, sagittal, coronal and transverse from left to right. The solid lines represent group mean angles and the dashed lines are one standard deviation above and below the mean. Blue and red lines represent the dominant and non-dominant limbs, respectively.

5.3.2 The Hand Over Head Movement

Group mean (standard deviation) upper limb peak joint angles and joint excursions during the hand over head functional movement in healthy children are presented in Table 5.6.

5.3.2.1 Peak Joint Angles

The peak joint angles exhibited during the hand over head movement in healthy children are presented in Table 5.6. During the hand over head movement, the upper limb demonstrated similar degrees of shoulder flexion and extension in the horizontal plane, which was the smallest joint ROM required of the three planes of the shoulder. Shoulder joint elevation peak was greater than 90°, showing that the humerus moved higher than horizontal to pass the hand over the head. A substantial degree of shoulder joint internal and external rotation peaks appear to be required to execute the hand over head task (73°±13 and 86°±9 respectively, dominant limb). Elbow extension was not achieved during the hand over head movement as the elbow was flexed at all times during the movement. A greater degree of forearm supination than pronation was demonstrated during the movement. Wrist flexion and extension peak joint angles were similar to each other, as was the radial and ulnar deviation peaks which appear to be required to execute the hand over head movement. These two

Table 5.6 Mean (standard deviation) peak joint angles of the upper limb joint postures during the hand over head movement.

Joint Plane	Peak Joint Angle (°)		Joint Excursions (°)	
	Dominant	Non-Dominant	Dominant	Non-Dominant
Shoulder Joint Horizontal Flexion	64* (8)	68 (10)	121 (17)	132 (16)
Shoulder Joint Horizontal Extension	-57* (14)	-64 (14)		
Shoulder Joint Elevation Maximum	121 (11)	122 (10)	-	-
Shoulder Joint Internal Rotation	73 (13)	73 (13)	159 (13)	162 (16)
Shoulder Joint External Rotation	-86 (9)	-89 (12)		
Elbow Flexion	140* (6)	143 (8)	116 (10)	122 (9)
Elbow Extension	24 (8)	21 (9)		
Forearm Pronation	30 (19)	27 (17)	88 (18)	90 (16)
Forearm Supination	-58* (11)	-64 (10)		
Wrist Flexion	34* (14)	41 (15)	58 (15)	60 (15)
Wrist Extension	-24 (23)	-19 (20)		
Radial Deviation	18 (6)	19 (10)	30 (9)	31 (9)
Ulnar Deviation	-12 (5)	-12 (5)		

* = significant p value for dominance

joint plane peak joint angles were relatively small compared to those demonstrated at other joints.

5.3.2.2 Joint Excursions

The greatest range of joint excursion was demonstrated in shoulder rotation, indicating that the hand over head movement predominantly involved motion in the longitudinal axis of the shoulder. Large excursions of motion were also demonstrated at the shoulder in the horizontal plane, for shoulder joint elevation, elbow flexion and forearm pronation and supination (greater than 90°).

5.3.2.3 Between-limb Differences in Peak Joint Angles

There were differences relating to limb dominance in 5 out of the 13 peak joint angles measured (see Table 5.6). All of those 5 variables showed the dominant limb peak joint angles to be less than the non-dominant limb.

5.3.2.4 Repeatability of Peak Joint Angles

There was no main effect for trial in peak joint angles during the hand over head movement. Intraclass correlations revealed that the strength of agreement of each peak joint angle was moderate or better (ICC ≥ 0.47) for both the dominant and non-dominant limbs (Table 5.7). These results suggest that movements were repeatable within subjects across 3 repeats within the same testing session.

Table 5.7 Intraclass correlation coefficients (ICC) and confidence intervals (CI) for peak joint angles during the hand over head movement in healthy children.

Joint Plane	Dominant		Non-Dominant	
	ICC	(CI)	ICC	(CI)
Shoulder Joint Horizontal Flexion	0.579	(0.324-0.786)	0.469	(0.196-0.715)
Shoulder Joint Horizontal Extension	0.669	(0.439-0.838)	0.527	(0.261-0.753)
Shoulder Joint Elevation Maximum	0.895	(0.794-0.953)	0.841	(0.700-0.928)
Shoulder Internal Rotation	0.676	(0.449-0.842)	0.661	(0.429-0.834)
Shoulder External Rotation	0.88	(0.768-0.946)	0.791	(0.619-0.903)
Elbow Flexion	0.938	(0.874-0.973)	0.965	(0.928-0.985)
Elbow Extension	0.708	(0.494-0.860)	0.750	(0.555-0.882)
Forearm Pronation	0.808	(0.646-0.912)	0.671	(0.442-0.839)
Forearm Supination	0.774	(0.592-0.895)	0.741	(0.541-0.877)
Wrist Flexion	0.708	(0.494-0.860)	0.763	(0.575-0.889)
Wrist Extension	0.894	(0.793-0.953)	0.618	(0.373-0.809)
Radial Deviation	0.829	(0.680-0.992)	0.892	(0.790-0.952)
Ulnar Deviation	0.615	(0.369-0.807)	0.574	(0.318-0.783)

5.3.2.5 Timing of Peak Joint Angles

The timing of peak joint angles during the hand over head movement is presented in Table 5.8. All of the peak joint angles occurred between 34-72% of the movement cycle. The timing of the shoulder joint horizontal extension, elbow flexion, forearm pronation, wrist extension and radial deviation peaks were similar to each other, occurring between 69-72% of the movement duration. This may indicate the point at which the upper limb reaches the back of the head, just before it starts to return to the side of the body. The timing of shoulder joint elevation, shoulder joint internal rotation and external rotation occurred close to each other, between 54-63% of the movement duration, which may correspond to the hand being on top of the head. Shoulder joint horizontal flexion and ulnar deviation peak joint angles occurred the earliest, at 38% and 35% of the movement duration, respectively.

5.3.2.6 Between-limb Differences in Timing of Peak Joint Angles

There were no significant differences between the dominant and non-dominant limbs in the timing of any of the peak joint angles during the hand over head movement.

5.3.2.7 Repeatability of Timing of Peak Joint Angles

The ANOVA found no significant differences between the repeated trials for the timing of the peak joint angles during the hand over head movement.

Table 5.8 Group mean (standard deviation) relative timing of upper limb peak joint postures during the hand over head movement.

Joint Plane	Timing of Peak Joint Angle (%)	
	Dominant	Non-Dominant
Shoulder Joint Horizontal Flexion	38 (17)	34 (12)
Shoulder Joint Horizontal Extension	72 (20)	65 (28)
Shoulder Joint Elevation Maximum	55 (5)	55 (6)
Shoulder Joint Internal Rotation	54‡ (24)	59 (26)
Shoulder Joint External Rotation	63 (9)	65 (10)
Elbow Flexion	70 (6)	72 (15)
Elbow Extension	46 (25)	39 (29)
Forearm Pronation	71 (20)	72 (15)
Forearm Supination	44 (16)	42 (18)
Wrist Flexion	49 (23)	59 (26)
Wrist Extension	69 (13)	63 (18)
Radial Deviation	69 (10)	70 (8)
Ulnar Deviation	35 (24)	38 (25)

‡ = significant interaction of factors ($p<0.05$)

Furthermore, there were no significant limb×repeat interaction effects for the timing of any of the peak joint angles during the hand over head movement. Intraclass correlations however revealed that the strength of agreement of the timing of the peak joint angles ranged between poor to moderate (ICC's between -0.16 and 0.59, see Table 5.9). Therefore there was some variation of when the peak joint angles occurred during the movement within the group.

5.3.2.8 Repeatability of the Waveforms

The repeatability of the waveforms of the hand over head movement was analysed using the Adjusted Coefficient of Multiple Correlations statistic (CMC), described in Chapter 3. Group means (standard deviations) of the within-subject CMC for hand to mouth movement are presented in Table 5.10. Shoulder joint horizontal flexion/extension, shoulder joint elevation, shoulder rotation and elbow flexion/extension repeatability was excellent for the dominant and non-dominant limbs, with the dominant limb showing slightly higher repeatability (r = 0.92-0.97 dominant limb, r = 0.89-0.96 non-dominant limb). Forearm pronation/supination and radial/ulnar deviation demonstrated CMCs of 0.79-0.84 and 0.82, however are still considered to be highly repeatable as reported by Steinwender and colleagues (2000). Wrist flexion and extension demonstrated moderate repeatability, which can be seen by the large standard deviations of the normative graphs for hand over head movement, indicating larger variability within the group for these joint planes (Figure 5.5).

Table 5.9 Intraclass correlation coefficients (ICC) and confidence intervals (CI) for the timing of peak joint angles during the hand over head movement in healthy children.

Joint Plane	Dominant ICC (CI)	Non-Dominant ICC (CI)
Shoulder Joint Horizontal Flexion	0.434(0.159-0.692)	0.102(-0.138-0.417)
Shoulder Joint Horizontal Extension	-0.156(-0.314-0.116)	0.079(-0.155-0.394)
Shoulder Joint Elevation Maximum	0.220(-0.430-0.525)	0.351(0.075-0.631)
Shoulder Internal Rotation	-0.146(-0.308-0.130)	0.000(-0.212-0.310)
Shoulder External Rotation	0.481(0.210-0.724)	0.560(0.300-0.774)
Elbow Flexion	0.363(0.087-0.640)	0.594(0.341-0.795)
Elbow Extension	0.089(-0.272-0.204)	0.047(-0.179-0.360)
Forearm Pronation	0.558(0.298-0.773)	-0.049(-0.246-0.252)
Forearm Supination	0.265(-0.004-0.564)	0.525(0.260-0.753)
Wrist Flexion	0.276(0.006-0.573)	0.510(0.242-0.743)
Wrist Extension	-0.001(-0.213-0.308)	0.116(-0.127-0.430)
Radial Deviation	0.248(-0.019-0.549)	0.442(0.147-0.683)
Ulnar Deviation	0.071(-0.162-0.385)	0.188(-0.070-0.498)

Table 5.10 Group mean (standard deviation) Adjusted Coefficient of Multiple Correlations for the hand over head movement.

Joint Plane	Within-Subject	
	Dominant	Non-Dominant
Shoulder Joint Horizontal Flex/Ext	0.92 (0.1)	0.89 (0.1)
Shoulder Joint Elevation	0.97 (0.0)	0.96 (0.0)
Shoulder Joint Rotation	0.94 (0.0)	0.92 (0.1)
Elbow Flexion/Ext	0.96 (0.0)	0.95 (0.0)
Forearm Pro/Sup	0.84 (0.1)	0.79 (0.2)
Wrist Flex/Ext	0.66 (0.2)	0.68 (0.2)
Radial/Ulnar Dev	0.82 (0.2)	0.84 (0.1)

5.3.2.9 Normative Data Waveforms

The entire dataset of three repeats for twenty subjects were averaged to give mean and standard deviation waveforms for upper limb joints for both dominant and non-dominant limbs. This data is displayed graphically (Figure 5.5) and provides normative data waveforms of the upper limbs during the hand over head movement in healthy children.

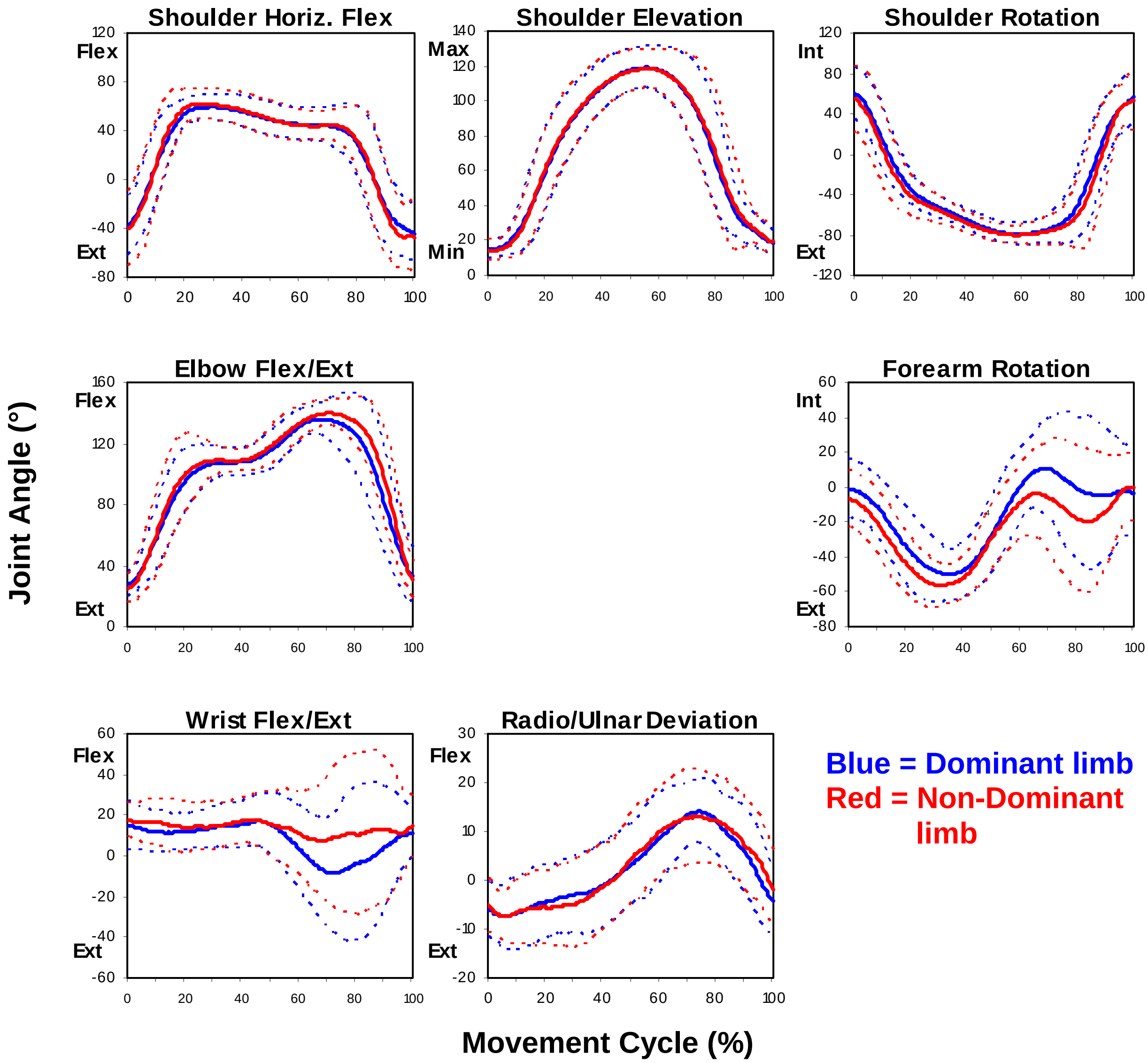

Figure 5.5 Time-normalised graphs of upper limb joint kinematics during the hand over head movement in healthy children. The graphs are arranged so that each row contains data from the same joint, and the planes of movement are arranged in columns across the page, sagittal, coronal and transverse from left to right. The solid lines represent the group mean angles and the dashed lines are one standard deviation above and below the mean. Blue and red lines represent the dominant and non-dominant limbs respectively.

5.4 DISCUSSION

Functional upper limb movement in children with movement disorders is most commonly assessed in clinical practice using qualitative assessment tools, to assist treatment decision making. This study was undertaken to examine a methodology of quantitative measurement of functional upper limb movements in healthy children for future application to children with movement disorders.

The peak joint angles and their relative timing during the movement, as well as joint excursions of motion demonstrated were examined during two upper limb functional movements in 20 healthy children. The effect of limb dominance and within-subject repeatability of peak joint angles as well as the timing of the peak joint angles and waveform repeatability for the group were examined. The findings of the kinematic analysis of two functional upper limb movements in children are presented to provide data for comparison to populations with movement disorders. This methodology and normative data may be used to provide quantitative information to clinicians to assist treatment decision making to optimise outcomes of intervention to maximise upper limb function for children with movement disorders.

5.4.1 Peak Joint Angles

The peak joint angles of healthy children during functional movements were measured to further knowledge on how healthy children use their upper limbs during every day tasks. Previous authors have reported functional upper limb movements to describe the peak joint angles of adults and children (Fitoussi et al., 2006, Mackey et al., 2005, Mackey et al., 2006, Magermans et al., 2005, McIntosh et al., 2002, Petuskey et al., 2007, Rau, 2000, Safaee-Rad, 1990b). Some comparisons can be made between data measured in the current study and previous work measuring similar movements, however few studies have measured the same movements as those presented here.

5.4.1.1 Upper Limb Motion in Adults

Magermans and colleagues (2005) measured comparable functional upper limb movements that are comparable with the current study using an electrogoniometer in healthy female adults. These movements were the eating with a spoon movement (similar to hand to mouth movement reported here) and the combing hair movement (similar to hand over head movement reported here). Comparing these two movements to those of the current study, differences in results were found for all equivalent measures between the populations with two exceptions (see Table 5.11). Those variables that were found to be similar were peak shoulder joint horizontal flexion during the combing hair movement (comparable to hand over head movement) and elbow flexion findings for both functional movements. It is difficult to say whether the differences found between the adult population performing the two functional movements described and the comparable two functional movements in this study are due to differences between populations, differences in measurement techniques or discrete differences in the movements. There was no trend present, as some measures for the adult population were greater than healthy children and some were less.

5.4.1.2 Upper Limb Motion in Children

Three dimensional motion analysis findings of upper limb functional movements in a smaller cohort of healthy children and children with movement disorders have been reported previously by Mackey et al., (2006). During hand to mouth and hand to head movements, Mackey and colleagues (2006) reported greater elbow flexion peak joint angles in their cohort of healthy children. Forearm pronation findings of Mackey and colleagues (2006) show good agreement for the hand to mouth movements measured in healthy children (5±32° and 4±20° respectively, non-dominant limb). For the hand to head movement, the forearm pronation peak joint angle measures differed with the current study reporting lower values, as was the case with forearm supination peak joint angles for both movements. These

Table 5.11 Comparison of current study results to those of Magermans et al., (2005) during functional tasks. Upper limb peak joint angles are presented for the hand to mouth and hand over head movements in this study and similar movements 'eating with spoon' and combing hair' movements described by Magermans et al., (2005).

	Peak Joint Angle (°)			
Joint Plane	Hand to Mouth	Eating with Spoon	Hand over Head	Combing Hair
Shoulder Joint Horizontal Flexion	88 (10)	60.0 (14.4)	64 (8)	58.5 (14.3)
Shoulder Joint Elevation	45 (9)	73.5 (12.6)	121 (11)	89.8 (9.3)
Shoulder Joint External Rotation	-57 (11)	-49.3 (14.0)	-86 (9)	-70.2 (18.9)
Elbow Flexion	134 (5)	131.5 (7.5)	140 (6)	135.7 (14.6)
Forearm Pronation	5 (20)	71.9 (31.4)	30 (19)	99.9 (27.8)

conflicting findings cannot be explained by differences in joint axes definitions.

The differences of elbow joint flexion peak joint angles between Mackey and colleagues (2006) and the current study may be related to the definition of the zero position (at elbow extension). Skin movement artefact about the elbow where the markers defining the local coordinate system are located are also a potential source of error. A better location for these markers would potentially improve these measurement comparisons in future research.

Differences between forearm rotation found for hand *over* head movement and that reported by Mackey and colleagues (2006) for the hand *to* head movement are likely to be related to the different requirements of the hand orientation for each movement. The navigation of the hand *over* the head demands a different posture of the forearm than only having to touch the front of the head with the hand. Differences in the movements (for example hand *over* head movement and hand *to* head movement) are the most likely reason for differences found between studies for peak joint angles during the functional movements.

5.4.2 Repeatability of Peak Joint Angles

The current study measured three repeats of the upper limb functional movements for each subject. Analysis of variance and intraclass correlation investigations showed that the peak joint angles measured during the hand to mouth and hand over head tasks for all upper limb joints were repeatable within subjects and had moderate or better strength of agreement across all measures in a healthy child population (data grouped according to limb dominance) with one exception, being wrist extension in the non-dominant limb during the hand to mouth movement. This provides evidence that the measurement methods of the two functional movements performed by healthy children are repeatable.

5.4.3 Timing of Peak Joint Angles

The timing of the peak joint angles was investigated to decipher whether the group achieved these joint angles at the same time during the movement, to identify if the peak joint angles marked meaningful events during the movements. The timing of peak joint angles was found to be repeatable when investigated with a 2 factor analysis of variance test, with one exception (elbow extension) during the hand to mouth movement. All other measures of the timing of peak joint angles were found to have no significant differences within the group studied. Further investigation of the timing of the peak joint angles with intraclass correlations revealed that there was only fair or poor agreement for the group for most peak joint angles measured during the two movements. The timing of the peak joint angles therefore does not appear to be important to the execution of the two tasks measured in a healthy child population.

5.4.4 Between-limb Differences

Differences in peak joint angles between the dominant and non-dominant limbs were found for both functional movements. The absolute values of the differences have been considered by previous authors to determine whether or not they are clinically significant (Mackey et al., 2006, Petuskey et al., 2007). The concept of clinical significance is whether or not a measure would make a difference to clinical decision making. For both movements, the largest significant difference in peak joint angles was 7° between dominant and non-dominant limbs. Anatomical movements measured in Chapter 4 showed that although significant differences were found relative to limb dominance, the absolute value of all differences was 4° or less. Statistically significant differences between limbs have been ignored previously when the absolute differences were small, being described as not having clinical significance (Mackey et al., 2006, Petuskey et al., 2007).

As discussed in Chapter 4, the increased use of the dominant limb relative to the non-dominant limb may cause decreased joint range, with relative shortening the musculotendonous units. If this theory is valid, then inspection of which joint planes show greater reduction in dominant limb range compared to the non-dominant limb may provide insight to which joints are used the most in activities of daily living.

Petuskey and colleagues (2007) measured kinematics during upper limb functional movements in 51 healthy children. The authors found statistically significant differences between dominant and non-dominant limb joint positions at the point of task achievement (defined as the point where the functional task was achieved). Despite this, the authors combined the data of the dominant and non-dominant limbs, reasoning that the magnitude of the difference was 6° or less.

Mackey and others (2006) measured upper limb kinematics in children with hemiplegia and healthy children. These authors found no differences between the dominant and non-dominant limbs in ROM of the healthy children for any of the three functional movements measured (hand to mouth, hand *to* head and a reaching task) in 10 subjects.

In the current study the differences found between dominant and non-dominant limb kinematics were small compared to the ROM required to perform these movements. Dominant and non-dominant data were presented separately in the current study to describe upper limb movement in healthy children. This was guided by the differences found in the ROM demonstrated, which was generally smaller for the dominant limb; and the comparable or higher repeatability of the dominant limb waveforms for both movements.

5.4.5 Functional Movements and Available Joint ROM

The upper limb joints did not utilise their full joint ROM during the two functional movements measured. Peak joint angles measured between the two movements differed, which are related to the different requirements of the movements. For example, shoulder joint elevation during hand over head movement was greater than during hand to mouth movement, as the upper arm was lifted up higher to allow the hand to reach the top of the head. Figure 5.6 presents the joint excursions of motions measured during the two functional movements as percentages of the joint ROM measured during the anatomical movements reported in Chapter 4 in the same cohort of children. The hand over head movement used a greater amount of available ROM for all joints measured. Therefore the hand over head movement can be considered to be more demanding than the hand to mouth movement based on greater joint motion required to execute the movement. These findings suggest that the hand over head movement may be better than the hand to mouth movement to assess upper limb function.

5.4.6 Waveform Repeatability

The continuum of joint angles throughout the duration of the functional movements was investigated to identify whether or not these movements

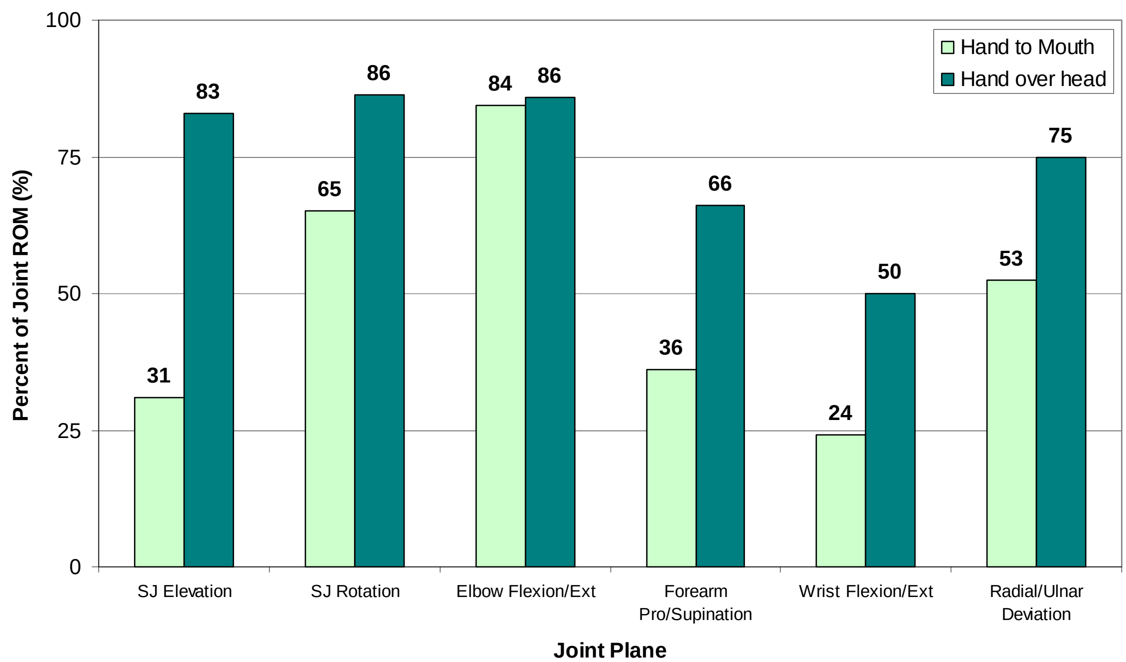

Figure 5.6 Percent of anatomical ROM used during the hand to mouth and hand over head movements in healthy children in the dominant limb.

were repeatable both within subjects. The CMC statistic was used to investigate the repeatability of waveform data. Within-subjects means and standard deviation waveforms were repeatable in both functional movements (CMC > 0.65), with the exception of the wrist flexion/extension waveform during the hand to mouth movement for both the dominant and the non-dominant limb (CMC = 0.56±0.2 and 0.46±0.2 respectively). This shows that within subjects, the hand to mouth movement was executed the same way over three repeats with the exception of wrist flexion/extension. The CMC statistic is directly related to the magnitude of the joint ROM, and in the case of the wrist flexion/extension and radio/ulnar deviation the ROM were low for the hand to mouth movement. Therefore the repeatability of the wrist motion may be underestimated by this measure of repeatability.

There was some increased variability of the normative waveforms for the hand to mouth movement at the beginning and end of the movements for shoulder and forearm rotation, and shoulder horizontal flexion. This indicates that the subjects start and finish positions were less consistent than when the hand was touching the mouth, in the mid section of the waveforms.

For the hand over head movement, within subjects, the movement was executed the same way over three repeats for all joint planes of the upper limb. Kadaba and others (1989) reported that adult gait was a repeatable functional lower limb task as the CMC's of the waveforms of three dimensional motion analysis data were above 0.65 for all pelvis and joint angles of the lower limb. In comparison, the repeatability of the upper limb functional movements represented by the CMC values of the movement waveforms in this study can be considered sufficiently repeatable for use in a clinical setting. The decreased repeatability of wrist flexion/extension during the hand to mouth movement should be kept in mind if this movement is used clinically to compare normative to pathological movement.

Previous studies have measured both limbs of hemiplegic children during functional movements using motion analysis and assessed the waveform repeatability using CMC's. Fitoussi et al., (2006) measured hand to mouth movement repeatability and found excellent repeatability for all measures of upper limb joints ($r > 0.84$) with the exception of shoulder axial rotation ($r = 0.82$) and radio/ulnar deviation ($r = 0.68$). These measures included the hemiplegic side which makes it difficult to compare to the current findings, as limited pathological movement with mechanical constraints (for example muscle contractures) may elicit more repeatable movements than that of healthy children. What is common between Fitoussi et al., (2006) and the current study is that there are repeatable components of upper limb movement using three dimensional motion analysis to measure healthy child populations and those with movement disorders.

Rab and others (2002) presented representative graphs of hand to mouth movement in 47 children (94 limbs) aged 5-19 years of age. Time normalised waveforms of mean ± one standard deviation of shoulder flexion, abduction, rotation and elbow flexion showed a maximum standard deviation of 25° from the mean. The authors stated that this magnitude of variability or less implied reproducibility of the methods used and of the functional movements demonstrated by the subjects. In the current study, three of the peak joint angles measured during the hand to mouth movement had standard deviations that were marginally greater than 25°. Closer inspection of the data showed shoulder joint horizontal flexion and shoulder joint rotation standard deviation to be greater than 25° at the beginning and end of the movement (0-23% and 80-100% of movement duration). This correlates to the regions of gimbal lock when the arm is near vertical. There was also increased variation of elbow flexion angle between 78-85% of hand to mouth movement. All other joints measured had standard deviations of 25° or less and are therefore considered repeatable, based on the definition of Rab and others (2002).

For the hand over head movement, there is greater variation in forearm rotation and wrist flexion/extension from approximately 60% of the movement duration, as observed by the mean waveforms (Figure 5.5). There is also some increased variation of elbow flexion angle from around 70-90% of movement duration. It is supposed that the variation in the hand over head movement waveforms at these joints occurred after the hand had passed over the top of the head, when the hand was returning to the start position, that is, after the point of task achievement. The event of the hand on top of the head during the movement was not measured however. It appears that it would be useful to mark key events, for example when the hand is on top of the head, to further understand the upper limb movement pattern, and allow measurement of repeatability of different phases of the movement.

The waveforms for forearm pro/supination were more repeatable for the hand over head movement than the hand to mouth movement (CMC = 0.84±0.1; 0.67±0.2 respectively; dominant limb). This was an interesting result considering the large standard deviations evident in the last 40% of the hand over head movement (see figure 6). Forearm rotation moved through small joint excursion during the hand to mouth movement which may contribute to these results (Kadaba et al., 1989). As suggested earlier, identification of an event during the movement would allow segmentation of the movements into phases and therefore permit closer study of each phase of the movement. As the hand over head movement was found to be more challenging than the hand to mouth movement in terms of the proportion of joint ROM required to complete the movement, it is suggested that the hand over head movement would be better suited to assess function than the hand to mouth movement.

5.5 Conclusions

For measurement of functional upper limb movements using three dimensional motion analysis, the results of this study suggest that the two functional movements measured are repeatable in healthy children. To allow comparison of results between studies using three dimensional motion analysis, there is a need to standardise methods of joint definitions, the movements analysed and calibrations of zero positions of the joints.

The excursions of motions measured during both functional movements presented in the current study were repeatable and can be used for comparison to other child populations. The hand over head movement excursions of motion were at least 50% of available ROM for the upper limb joints and required greater joint excursions of motion than the hand to mouth movement.

Peak joint angles demonstrated during functional movements were found to be repeatable when data were grouped into dominant and non-dominant limbs for healthy children, however the presented values of repeatability should be consulted to determine whether disordered movement is significantly different to the normative data presented here. Some differences between the dominant and non-dominant limbs were found during the functional movements measured. These findings suggest that dominant and non-dominant limb data should be presented separately when investigating healthy child arm movements.

The non-dominant limb showed similar or less repeatability for all measures for both functional movements, which showed excellent repeatability for all measures except for wrist flexion/extension during the hand to mouth movement.

It may be useful to define key events during upper limb functional movements using three dimensional motion analysis to further quantify repeatability in different phases of the movements. The normative waveform data presented provide norms for comparison to pathological movement, which may be used for clinical decision making. It appears that it is important to identify the excursions, joint positions at certain key events during the movement, and the repeatability of the movement investigated to appreciate any differences between data sets. Future research measuring children with movement disorders is needed to establish whether the movements and methods used are sensitive enough to identify differences between populations and guide clinical decision making.

CHAPTER SIX

SUMMARY AND FINAL CONCLUSIONS

6.1 BACKGROUND

Cerebral palsy is the most common cause of childhood disability (Carnahan et al., 2007) and can impair upper limb function. Therefore impaired upper limb function can impact on a person's ability to function independently during activities of daily living and has been classified as a component of disability by the World Health Organisation's International Classification of Functioning, Disability and Health (ICF).

Current assessment of upper limb function in the clinical setting predominantly uses qualitative assessment measurement tools (Beckung and Hagberg, 2002, Chin et al., 2005). The introduction of three dimensional motion analysis to assess lower limb movement disorders greatly improved outcomes of children with cerebral palsy by increasing knowledge of biomechanical characteristics of the lower limbs during walking (Buckley, 1996). Quantitative three dimensional motion analysis assessment can accurately quantify upper limb movement during functional movements; and has the potential to further knowledge of functional upper limb movement (Rau, 2000). This knowledge may improve outcomes for people with upper limb movement impairments, similarly to that shown for lower limb movement disorders with the implementation of clinical three dimensional gait analysis.

6.2 AIMS

The aim of this thesis was to determine repeatability of three dimensional upper limb anatomical ROM and functional movements and provide a normative dataset for healthy children. Such findings would advance current knowledge of the biomechanics of upper limb function in healthy children; and data presented would provide a basis for comparison to children with movement limitations in future research and clinical practice.

6.3 HYPOTHESES

It was hypothesised that maximum joint angles during anatomical movements; and peak joint angles, their timing and also the joint angles throughout the two functional movements (waveforms) were performed similarly over repeated measures in a healthy child population.

The null hypothesis was assumed regarding between limb differences, that is, that no difference would exist between dominant and non-dominant limbs of healthy children when measured with three dimensional motion analysis during anatomical and functional upper limb movements.

6.4 METHODS

A protocol to measure upper limb movement using three dimensional motion analysis and the UNSW upper limb kinematic model was used in a population of 20 healthy children. Data were acquired and presented to describe maximum joint angles and joint ROM during anatomical movements, as well as peak joint angles and joint excursions during functional movements. Normative data were presented to describe upper limb motion in healthy children during two functional tasks.

Between-trial repeatability was investigated for maximum joint angles and resultant joint ROM during the anatomical movements. Furthermore, peak joint angles and joint excursions during two functional tasks were examined to establish if the children demonstrated the same joint angles when asked to repeat the upper limb movements described in this study. Reproducibility was assessed for strength of agreement of multiple measures for the group. Data were analysed separately for dominant and non-dominant limbs to investigate if there were any differences in kinematics relating to limb dominance.

6.5 SUMMARY OF FINDINGS

6.5.1 Three Dimensional Upper Limb Motion Analysis in Healthy Children

The UNSW kinematic upper limb model was successfully used to measure three dimensional anatomical and functional upper limb movements in healthy children.

6.5.1.1 Anatomical Movements

The joint ROM's found during the anatomical movements were comparable to adult joint ROM's reported by McIntosh and others (2002) using the same kinematic model and methodology, indicating that healthy adults and children have similar joint ranges of motion. Elbow and wrist flexion/extension in the unaffected limb of children with cerebral palsy using the same kinematic model and methodology (Dwan et al., 2002) was reduced compared to healthy child upper limb joint ROM found in the current study. The maximum joint angles and joint ROM data during anatomical movements reported in Chapter 4 provide normative anatomical ROM data for upper limb joints during active movement in healthy children.

6.5.1.2 Functional Movements

Measures of peak joint angles and joint excursions during functional movements reported in Chapter 5 were different to those previously reported using an electrogoniometer in adults during similar functional upper limb movements (Magermans et al., 2005). It was unclear whether differences in findings were related to differences in movements performed, between populations or measurement techniques used. Mackey and colleagues (2006) measured upper limb motion in healthy children during similar functional measures and reported good agreement with Chapter 5 findings for forearm pronation during the hand to mouth movement, however other measures differed from the current study. Standardisation of the definition of the joint angles where the zero values are defined during the anatomical axis calibration, such as the methods developed for the current study may improve between-study comparability.

The findings of peak joint angles, timing of peak joint angles and joint excursions of motion during functional movements presented in Chapter 5 provide normative biomechanical data of healthy children's upper limb movement during two functional tasks.

6.5.2 Limb Dominance

Differences between dominant and non-dominant limbs were found in some joints in both the anatomical and functional movement measures. No single joint showed a difference between dominant and non-dominant limbs across all movements measured. Of all movements studied, the hand to mouth showed the least between limb differences. Joints that showed no differences between maximum or peak joint angles across all conditions were wrist extension and radial deviation. Shoulder elevation measured during the anatomical movements also demonstrated no difference in maximum joint angles between the dominant and non-dominant limbs. Therefore, the null hypothesis that there was no difference in between the dominant and non-dominant limb of healthy children when measured with three dimensional motion analysis during anatomical and functional upper limb movements in a healthy child population was rejected.

6.5.3 Repeatability

6.5.3.1 Peak Joint Angles

All peak joint angles measured during anatomical and functional movements were found to be repeatable in this population of healthy children, with moderate or better strength of agreement of group measures. These results suggest that the methods used here are reliable for investigating upper limb kinematics in this population and support the hypotheses that 1) healthy children perform reproducible upper limb maximum joint angles over repeated trials, as measured by three dimensional motion analysis during anatomical movements; and 2) healthy children perform reproducible upper limb peak joint angles over repeated trials during hand to mouth and hand over head functional movements.

6.5.3.2 Timing of Peak Joint Angles

The timing of the peak joint angles during the two functional movements were repeatable for all measures using a 2 factor analysis of variance, however the intraclass correlation findings show that healthy children do not reliably reach the peak joint angles at consistent times during the movement durations. In consideration of this, the hypothesis that the timing of peak joint angles during hand to mouth and hand over head movements are reproducible in healthy children is rejected. The significance of the timing of peak joint angles may become more apparent with investigation of pathological movement; and would allow comment on the coordination of joints during functional movements.

6.5.3.3 Movement Waveforms of Functional Tasks

Within-subject repeatability of waveforms (joint kinematics throughout the duration of the functional movements) was shown to be repeatable across trials, with the exception of the wrist flexion/extension waveform during the hand to mouth movement for both the dominant and the non-dominant limb. Besides this exception, functional movements within subjects were executed the same way over three repeats within a test session. The hypothesis that joint angles throughout the two functional movements measured would be reproducible over multiple repeats in healthy children was therefore accepted for all joint angles with the exception of wrist flexion/extension during the hand to mouth movement.

6.6 Final Conclusions

This thesis has produced normative kinematic data for upper limb motion in healthy children. The within-subject data during anatomical and functional movements (with one exception) were repeatable. These results provide evidence that developed neuromuscular motor patterns exist in the upper limbs for functional movements in healthy children within individuals. This thesis also identified that differences exist between dominant and non-dominant limbs in healthy children for upper limb maximum joint angles and the performance of functional movements.

6.7 Clinical Relevance

This data has clinical value, for comparison with people and populations with movement disorders to understand dysfunction and guide clinical decision making. The two functional movements examined in these studies are considered suitable for use in a clinical setting as healthy children were repeatable, suggesting that variations present in children with movement disorders would be due to the presence of pathology.

These studies found differences between dominant and non-dominant limbs during anatomical and functional movements of the upper limb. These results support previous studies (Mackey et al., 2006, Petuskey et al., 2007). Despite these findings dominant and non-dominant limb data have been combined previously, on the basis that the variation between values was relatively small. This practice has been done previously in the name of clinical significance. Combining data should be done with caution with consideration of sensitivity to identify pathological movement. With this in mind, dominant and non-dominant limb data were considered separately within this thesis.

6.8 FUTURE RESEARCH

Continued research and discussion on suitable conventions for kinematic modelling of upper limb movement is required to determine the most appropriate model that may perpetuate use of three dimensional motion analysis as a clinical tool. Continued development of modelling, methodology and therefore the resultant understanding of upper limb use from a biomechanical perspective will progress these techniques towards use in clinical settings.

The current study investigated two functional movements which mimicked activities of daily living. Further investigations of other functional tasks would further knowledge of the coordination of upper limb segments during dynamic use. Movements designed to elicit movements that are difficult for a population of interest, for example a movement that challenges forearm pronation/supination for comparison to children with cerebral palsy may prove to be a more informative movement to use in clinical settings to measure baseline and outcome measures for assessment of treatment.

Further research using three dimensional motion analysis of the upper limbs is required in other populations, such as children with cerebral palsy, traumatic brain injury and adults to allow comparison with the normative data presented in the current studies. Kinematic movement patterns associated with movement disorders may become evident, as has been demonstrated with three dimensional gait analysis in children with cerebral palsy with lower limb involvement. The identification of abnormal movement patterns in children with upper limb movement disorders has the potential to assist clinical decision making to achieve better outcomes for people with upper limb movement disorders, therefore improving their quality of life.

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APPENDIX A:

THESIS RELATED CONFERENCE PROCEEDINGS

I. Cerebral Palsy 2009 Abstract, Sydney, Australia, February 2009.

Kinematic Analysis of Two Functional Upper limb Tasks in Children.

Authors: Leanne Dwan, Andrew McIntosh, Kevin Lowe.

Abstract

Research methods in upper limb movement analysis are developing towards clinical tools. The identification of repeatable movement patterns of the upper limbs in a normal child population was investigated. Characteristics of movement patterns measured appeared repeatable, moving closer to forming a basis for comparison to pathologic movement.

Background

Recent research methods in the measurement of upper limb motion have progressed towards 3D motion analysis, to develop understanding of upper limb dynamic movement (Rau 2000). Upper limb movement measurement is complex (Veeger 2003, Rau 2000) due to the degrees of freedom available for movement completion (McIntosh et al. 2002, Schmidt 1999). There is a need to develop a valid protocol to measure function to allow application in clinical settings.

Objectives

The objective was to measure two functional movements of the upper limb in a normal child population.

Design

The study was a cohort of children aged 8 to 10 years, with no pathology, for kinematic analysis of two functional upper limb movements.

Participants/Setting

Subjects from local schools were invited to participate. 20 subjects took part in the study. Testing was done at the University of New South Wales Biomechanics and Gait Laboratory.

Materials/Methods

3D Motion capture was done using a Vicon Workstation system (Oxford Metrics). Two functional movements were measured: 1) Hand to mouth and 2) Hand over head. An upper limb model was run on the data (McIntosh 2002). Joint angles for shoulder, elbow and wrist joints, as well as the thorax segment were extracted. The maximum and minimum values for each degree of freedom were found. Time series data were then time-normalised, giving the timing of the maximums and minimums. Data from both limbs of each subject were measured and included for analysis, giving 40 limbs from 20 subjects. Comparisons between dominant and non-dominant limbs were investigated.

Results

Further analysis to establish repeatability within individuals of the angles measured is needed. When studying the timing of joint angle peaks during the movements, both movements demonstrated consistent timing of all maximum and minimum peaks of upper limb angles measured, except for the elbow extension peak.

Conclusions/Clinical Implications

The timing of peak joint angles of movements measured within a group of normal children appear to be largely consistent. Further investigation of dynamic functional upper limb tasks will provide clinicians with a tool to assist in the investigation and treatment of upper limb movement disorders.

a. Cerebral Palsy 2009 Poster, Sydney, Australia, February 2009.

Kinematic Analysis of Two Functional Upper Limb Tasks in Children.

THE UNIVERSITY OF NEW SOUTH WALES

L Dwan[1,2], A McIntosh[1], K Lowe[2], D Sturnieks[3].

[1] School of Risk & Safety Sciences, University of New South Wales, Sydney Australia.
[2] Sydney Childrens Hospital, Sydney Australia.
[3] Prince of Wales Medical Research Institute, Sydney Australia.

Abstract

Research methods in upper limb (UL) movement analysis are developing towards clinical tools. The identification of repeatable UL tasks in healthy children was investigated using the UNSW UL kinematic model. Characteristics of the movement patterns of two functional tasks measured are repeatable, allowing use of normative graphs for comparison to pathologic movement.

Background

Recent research methods in UL measurement have progressed towards 3D motion analysis, to develop understanding of UL dynamic movement [1]. UL movement measurement is complex [1,2] due to the degrees of freedom available for movement completion [3,4]

Objectives

To develop normative kinematic graphs of UL functional tasks in healthy children and compare dominant and non-dominant limbs.

Design

A descriptive 3D kinematic study of UL motion in healthy children during two functional tasks.

Participants/Setting

20 children aged 10.2 years ± 1.1 (range = 8.4-12.0) were recruited from local schools. Testing was done at the University of New South Wales Biomechanics and Gait Laboratory.

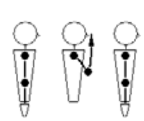

Figure 1 Hand to Mouth

Figure 2 3D reconstruction of Hand over Head

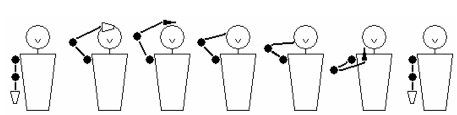

Figure 3 Hand over Head

Materials/Methods

Two functional UL tasks were performed 3 times per limb:
1) Hand to mouth (figure 1)
2) Hand over head (figure 2 & 3)

Movements were captured with a 3D Vicon Workstation system (Oxford Metrics) and the UNSW UL kinematic model was applied to the data [3].

Upper arm movement was modeled as humerus movement relative to the trunk. Shoulder, elbow and wrist joint angles were extracted. The time series data were time-normalised to task duration (waveforms; figure 4 & 5). Repeatability of waveforms were measured using the adjusted coefficient of multiple correlation (CMC's) [5].

Results

A 2 factor (dominance and repeats) ANOVA found all peak joint angles to be repeatable for both tasks.

- Differences between dominant and non-dominant limbs were found in 3 hand to mouth and 9 hand over head peak angles.
- Dominant and non-dominant limb time-normalised waveforms and CMC's for the hand over head task are presented in figure 4.
- Forearm rotation and wrist flexion had large variation in the later third of the hand over head task duration.
- Dominant limb waveforms of both tasks and CMC's presented in figure 5.
- Shoulder, elbow and wrist joint waveforms had moderate to high repeatability for both tasks.

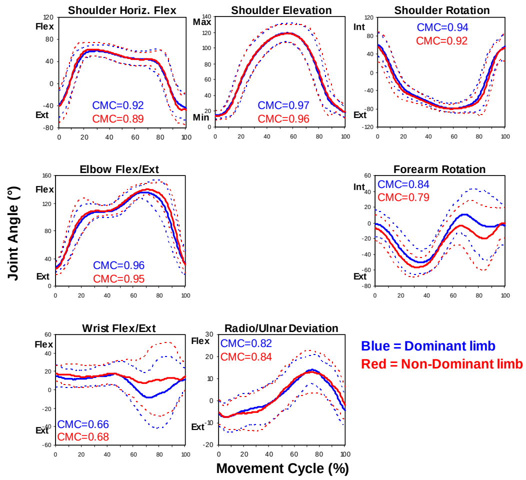

Figure 4 Hand over head waveforms of UL movement in healthy children. Solid lines are mean angles and dashed lines are 1 standard deviation above and below the mean. Blue = dominant limb. Red = non-dominant limb.

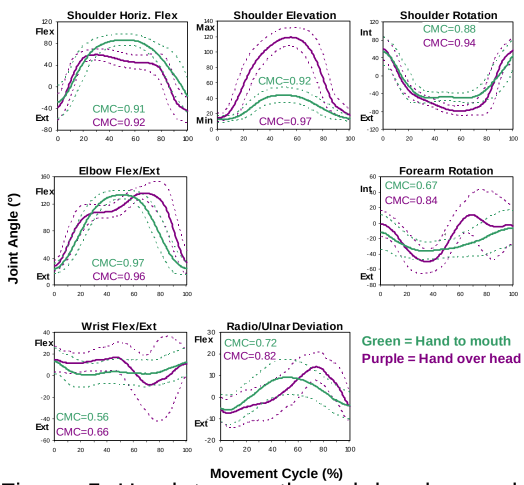

Figure 5 Hand to mouth and hand over head dominant limb waveforms of UL movement in healthy children. Solid lines are mean angles and dashed lines are 1 standard deviation above and below the mean. Green = hand to mouth. Purple = hand over head.

Conclusions/Clinical Implications

Dominant limb waveforms were either comparable or more repeatable than the non-dominant limb for both tasks. The hand over head task was more repeatable than the hand to mouth task in healthy children.

Further investigation of dynamic functional UL tasks will provide clinicians with a tool to assist the investigation and treatment of UL movement disorders. It is important to view motion analysis as a tool to assist clinical decision making; rather than a stand alone assessment of UL movement or ability. 3D motion analysis allows use of functional tasks to assess UL movement quantitatively. Careful selection of several functional tasks may be required to investigate certain movements of interest, for example elbow extension, which was not demonstrated in the two functional tasks presented here.

The results show that functional UL tasks in healthy children can be repeatable. Further research in this area, to identify optimal functional tasks for analysis, will allow techniques of UL motion analysis for use in the clinical setting, alongside clinical measures, to guide treatment planning for children with UL movement disorders.

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II. **Joint European Society of Motion Analysis in Adults and Children and Gait and Clinical Movement Analysis Society Meeting (JEGM06) Published Poster Abstract, Amsterdam, The Netherlands, September 2006. Published in Gait and Posture 24S/Published Posters, pS235-S238**

This work was also allowed to be presented at the Australasian Biomechanics Conference 6 (ABC6), Auckland New Zealand, February 2007 as a podium presentation.

KINEMATICS OF THE UPPER LIMB: A REACHING AND PLACING TASK WITH RESISTANCE IN CHILDREN

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Summary/conclusions

A resisted upper limb movement was investigated in a normal child population to determine movement patterns and repeatability. Results showed that the wrist is more extended when raising a heavier weight at shoulder height, with significant differences at the elbow and wrist when lowering different weights.

Introduction

Repeatable upper limb tasks and suitable measurement protocols are required to increase our understanding of upper limb function. There is a need in the clinical setting to consider how these assessments may be applied to special populations. Activities of daily living and functional tasks provide a natural starting point and these are used in some standard assessments, eg. QUEST [1]. The data presented here are part of a larger study on the biomechanical assessment of the upper limb in children.

Statement of clinical significance

The development of suitable upper limb assessments would assist in the identification of specific biomechanical impairments and evaluation of treatments for dysfunction in the upper limb, in cerebral palsy, stroke and traumatic brain injury.

Methods

The study was approved by the UNSW Human Research Ethics Advisory Committee. Children between the ages of 7 and 11 were recruited to the study. Using a stand with two positions for weight placement, the children were asked to perform a reach and place task. The weight was transferred from the low to the high position (the UP movement) and from high to low (DOWN movement). A peak elbow flexion (EF) during movements occurred due to an obstacle on the stand. Hand resistance was 0.1 and 0.8kg.

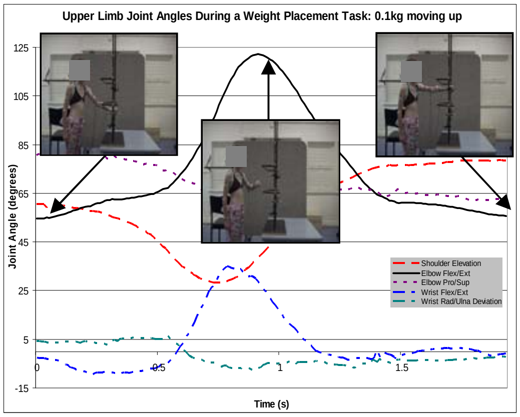


Figure 1. Upper limb kinematics during up movement

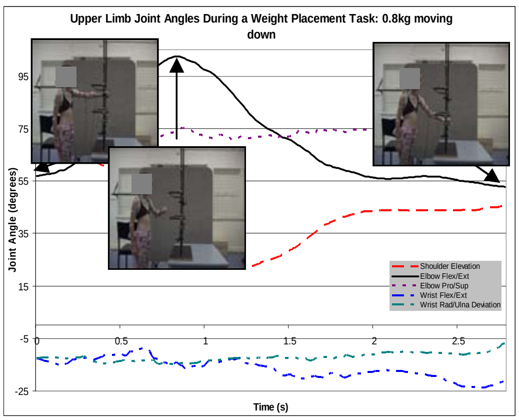


Figure 2. Upper limb kinematics during down movement.

Each task was repeated three times and motion analysis data were captured with a Vicon system (Workstation 4.6). A five segment model of the upper limb was used to measure shoulder, elbow, forearm and wrist motion [2]. Data were captured at 100 Hz. Data from 11 children during dominant limb movement are presented.

Results

Joint range of motion data during the movements are presented in table 1. Three key events analysed were 1) hand at low position, 2) peak elbow flexion and 3) hand at high position, which are presented in table 2. Mean of group data and standard deviation of the individual means are presented. 2-way ANOVAs were performed on data to identify significant differences.

Table 1. Joint range of motion during the UP and DOWN weight transfer movements (°).

Movement	UP						DOWN					
	Max		Min		Range		Max		Min		Range	
Weight	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg
Angle	Shoulder Elevation						Shoulder Elevation					
Mean	73	72	26	26	47	46	73	74	29	28	44	45
SD	7	6	8	7	9	8	6	6	8	5	7	4
Angle	Elbow Flex/Ext						Elbow Flex/Ext					
Mean	114	115	46	47	68	69	112	115	45	45	67	70
SD	12	11	9	8	9	10	10	9	8	8	8	11
Angle	Elbow Pro/Sup						Elbow Pro/Sup					
Mean	67	69	43	43	24	25	**66***	68	49	47	**17***	21
SD	11	11	13	14	14	10	11	12	8	10	6	7
Angle	Wrist Flex/Ext						Wrist Flex/Ext					
Mean	**3***	-3	-29	-29	**33***	26	-3	-3	-26	-28	24	25
SD	16	10	11	7	12	8	12	8	10	5	7	9

***** denotes a significant difference between 0.1kg and 0.8kg at $p < 0.05$.

Table 2. Key event data during the UP and DOWN weight transfer movements (°).

Movement	UP						DOWN					
Events	Low		Peak EF		High		Low		Peak EF		High	
Weight	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg	0.1kg	0.8kg
Angle	Shoulder Elevation						Shoulder Elevation					
Mean	48	50	34	34	72	71	49	48	40	42	72	71
SD	11	9	8	8	7	6	10	8	9	9	6	9
Angle	Elbow Flex/Ext						Elbow Flex/Ext					
Mean	48	51	114	115	51	52	**50***	57	112	113	47	45
SD	10	9	12	12	8	10	9	8	10	14	8	7
Angle	Elbow Pro/Sup						Elbow Pro/Sup					
Mean	64	64	50	53	52	50	60	62	56	53	**57***	53
SD	10	10	15	14	9	11	10	10	10	10	10	7
Angle	Wrist Flex/Ext						Wrist Flex/Ext					
Mean	-22	-24	-9	-11	**-5***	-14	**-16***	-20	-10	-7	-12	-14
SD	9	6	21	15	8	5	10	6	15	10	9	7

Units are degrees. ***** denotes a significant difference between 0.1kg and 0.8kg at $p < 0.05$.

Discussion

Movement patterns for each individual were repeatable. Joint range of motion data were mostly unaffected by increasing the hand resistance, except for wrist flexion/extension during the up movement, and pronation/supination in the down movement. During the down movement, elbow and wrist flexion/extension at the low position and pronation/supination at the high position were different between hand resistances. This data can be used comparatively for further research into dysfunctional upper limb movement.

References

[1] DeMatteo et al, (1993), Physical and Occupational Therapy in Pediatrics, 13(2), 1-18.
[2] McIntosh et al, (2002), Proceedings of ABC4, 84-85, Melbourne Australia.

a. Poster: JEGM06, Amsterdam, The Netherlands, September 2006.

Kinematics Of The Upper Limb: A Reaching and Placing Task With Resistance In Children

UNSW

Dwan, LN, McIntosh, AS.

School of Safety Science, University of New South Wales, Sydney, Australia

INTRODUCTION

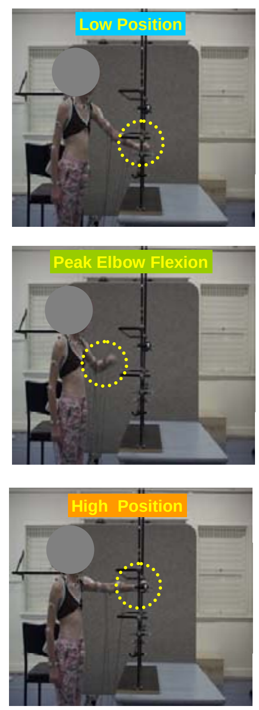
- There is a need to identify 1) repeatable upper limb tasks and 2) suitable measurement protocols to provide normative data.
- This would provide baseline data for comparison with upper limb movement disorders, such as in cerebral palsy, stroke and traumatic brain injury.
- Activities of daily living and functional tasks provide a natural starting point and these are used in some standard assessments, eg. QUEST [1].

METHODS

- Children between the ages of 7 and 11 were recruited to the study.
- Using a stand with two positions (high and low) for weight placement, the children were asked to perform a reach and place task.
- Each task was repeated three times and three dimensional motion analysis data were captured with a Vicon 612 system (Workstation 4.6).
- A five segment model of the upper limb was used to measure shoulder, elbow, forearm and wrist motion [2].
- The weight was transferred from the low to the high position (the UP movement) and from high to low (DOWN movement).
- A peak elbow flexion (EF) during movements occurred due to an obstacle on the stand.
- Hand resistance was 0.1 and 0.8kg.
- n = 11 children (dominant limb movement)
- frame rate = 100Hz

RESULTS

- Joint range of motion (ROM) data during the movements are presented in Chart 1.
- Three key events analysed were 1) hand at low position, 2) peak elbow flexion and 3) hand at high position. Wrist extension is presented in Chart 2.
- 2-way ANOVAs were performed on data to identify significant differences.



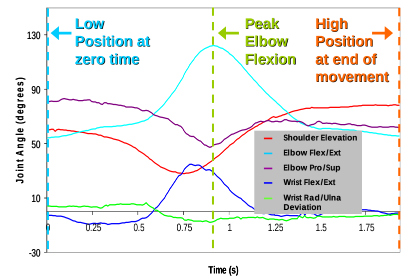


Figure 1. Time series data of upper limb kinematics during the up movement (one subject with 0.1kg hand resistance).

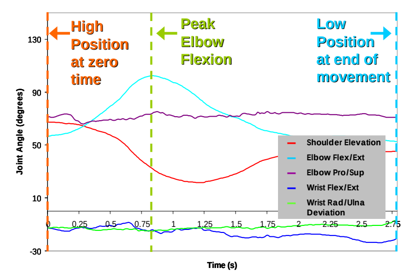


Figure 2. Time series data of upper limb kinematics during the down movement (one subject with 0.8kg hand resistance).

Chart 1. Mean joint ROM during weight transfer movements (* denotes a significant difference between 0.1kg and 0.8kg at $p < 0.05$).

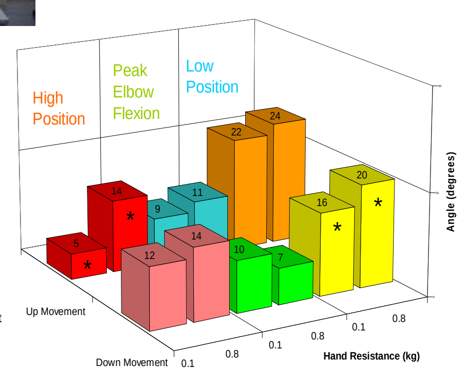


Chart 2. Key event Wrist Extension data during weight transfer movements (* denotes a significant difference between 0.1kg and 0.8kg at $p < 0.05$).

DISCUSSION

Movement patterns for each individual were repeatable. Joint ROM data were mostly unaffected by increasing the hand resistance, except for wrist flexion/extension during the up movement, and pronation/supination in the down movement. During the down movement, elbow and wrist flexion/extension at the low position and pronation/supination at the high position were different between hand resistances. This data can be used comparatively for further research into dysfunctional upper limb movement.

SUMMARY / CONCLUSIONS

A resisted upper limb movement was investigated in a normal child population to determine movement patterns and repeatability. Results showed that the movements studied had repeatable components within subjects, and within the group.

The data presented here are part of a larger study on the biomechanical assessment of the upper limb in children.

REFERENCES

[1] DeMatteo et al, (1993), Physical and Occupational Therapy in Pediatrics, 13(2), 1-18.

[2] McIntosh et al, (2002), Proceedings of ABC4, 84-85, Melbourne Australia.

Contact: Ms. Leanne Dwan, l.dwan@unsw.edu.au

APPENDIX B:

HUMAN RESEARCH ETHICS COMMITTEE APPROVAL

:

THE UNIVERSITY OF
NEW SOUTH WALES

HUMAN RESEARCHH ETHICS
COMMITTEE (HREC)

19th July, 2004

Human Research Ethics Advisory Panel 'H'
Application Approved

Associate Professor Chris Winder
School of Safety Science
Building B10, No2
UNSW

RE: **Quantitative Analysis of Upper Limb Range of Motion and Functional Tests in Children**
Reference Number: 8/04/01
Investigators: Mr Andrew McIntosh, Ms Leanne Dwan

At its meeting on 19th July, 2004, the Human Research Ethics Advisory Panel 'H' has recommended to your Head of School and the Human Research Ethics Committee that this project, being of minimal ethical impact, may proceed

This approval is valid for 12 months from this date.

....

Prof Arthur Ramer
Convenor,
Human Research Ethics Advisory Panel 'H'

APPENDIX C:

CATHOLIC EDUCATION OFFICE LETTER OF APPROVAL

CEO Sydney

Catholic Education Office, Sydney

38 RENWICK STREET, LEICHHARDT NSW • PO BOX 217, LEICHHARDT 2040 • PH (02) 9569 6111 • FAX (02) 9550 0052

3 June 2005

Deanne Dwan
Masters Candidate
School of Safety Science
University of New South Wales
SYDNEY NSW 2052

Dear Ms Dwan

Thank you for your application dated 24 May 2005 to conduct research in Catholic systemic schools in the Archdiocese of Sydney.

Permission is given for you to approach the Principals of the primary schools nominated, listed below, requesting participants for your study:

"Quantitative Analysis of upper Limb Range of motional and Functional Tasks in Children"

Please take copies for this approval latter to Principals of the schools you have listed. You will need to make arrangements with each participating Principal for the distribution of flyers to parents.

It is the prerogative of any Principal whom you might approach to decline your invitation to be involved in this study or to withdraw from involvement at any time.

The privacy of the school and that of any school personnel or students involved in your study must, of course, be preserved at all times and comply with requirements under the Commonwealth Privacy Amendment (Private Sector) Act 2000. You have indicated that researchers will have supervised contact with children. Please contact Carolyn Hadley on 9568 8492 to arrange for a Working with Children clearance.

When you have established your participating schools, please complete the attached form and return it to this office. It is a condition of approval that when your research has been completed you will forward a summary report of the findings and/or recommendations to this office as soon as practicable after results are to hand.

Please do not hesitate to contact me or Miss Evette Ashton at this office if there is any further information you require. I wish you well in this undertaking and look forward to learning about your findings.

Yours sincerely,

C Barrett

Christopher Barrett
Education Officer, Human Resources
on behalf of
Br Kelvin Canavan fms
EXECUTIVE DIRECTOR OF SCHOOLS

APPENDIX D:

LETTER TO PRINCIPALS INVITING CHILDREN TO PARTICIPATE

Principal
[ADDRESS]
To the Principal,

RE: DISTRIBUTING RECRUITMENT FLYERS FOR RESEARCH TO YOUR STUDENTS

I am a research student at the University of New South Wales, and I wish to investigate arm movement and function in children. This study is the beginning of investigations into how children with cerebral palsy use their arms, and how their arm use and function can be improved. In order to make comment on the arm use in children with pathology, there first needs to be a set of reference data for comparison. This is why I ask you to consider allowing me to invite your students to participate.

This research project has been approved by the University of New South Wales Human Ethics Advisory Committee. I have also passed a criminal record check, performed through my current employer as my work involves children.

Please find attached the flyer that I would like to have distributed to students aged from 8 to 10 years of age. I am happy to speak to the students about the project, if you think this would be suitable. If your approval is granted, I will supply all printed copies for students to take home to their parents or guardians, and interested parties can fill out the contact details section. The flyer can then be handed in at your school office, to be placed in a folder provided by me, which I would collect one to two weeks after the flyers are sent home.

Participation in the study will be out of school hours at the University of New South Wales, scheduled at the families' convenience.

I hope you are able to give your support to this research. I am happy to follow suggestions for delivery and collection of my flyers in a manner most convenient for your school and students. Please do not hesitate to contact me if you would like to discuss this further.

Regards,

Leanne Dwan BAppSc(Ex & Sp Sc)
Masters Candidate
School of Safety Science
University of New South Wales
Ph: 9385 5413

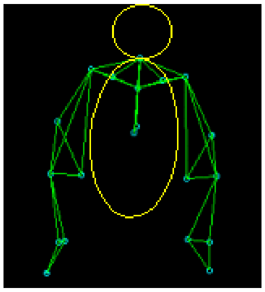
APPENDIX E:

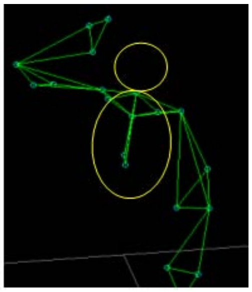
SUBJECT PARTICIPATION ADVERTISEMENT

SUBJECTS NEEDED

STUDY ON ARM MOVEMENTS AT

THE UNIVERSITY OF NEW SOUTH WALES





Dear Parent/Guardian,

My name is Leanne Dwan and I am a research student at the University of New South Wales. I am interested in studying the dynamics of arm movements and strength in children. I am currently looking for children between the ages of 7 and 11 to participate in my study, and would like to invite you to consider whether your child might participate.

The study will be conducted at the university campus in Kensington, and will take between 2 to 2½ hours, scheduled at your convenience. Small reflective markers will be placed on your child's arms and trunk and worn during the exercises, and electrodes will be placed over muscles to help us understand what muscles are being used. The exercises are safe and involve simple arm movements and strength measurements.

If you are interested in having your child participate in this study, or have any questions regarding this research, please contact me on the numbers below.

Leanne Dwan: [contact phone numbers]

APPENDIX F:

PARENT INFORMATION SHEET

The University of New South Wales
Participant Information and Consent Form
Quantitative Analysis of Upper Limb Range of Motion and
Functional Tests in Children
Approval No 8/04/01

Quantitative Analysis of Upper Limb Range of Motion and Functional Tests in Children

Your child is invited to participate in a study of arm movement and function. We hope to learn how to better describe arm movement and collect comparative data for future studies for kids with special needs. Your child was selected as a possible participant in this study because their school is close to the testing location.

If you decide that you would like your child to participate, they will have small reflective markers taped to specific positions on their arms and trunk. Your child will then be asked to perform several basic arm and hand movements, and also some exercises to test their strength. Activation patterns of the arm muscles will be measured by placing electrodes over selected muscles. The whole process should take between 2 and 2 ½ hours.

If your child's skin is sensitive to adhesives such as bandaids, then the tape used to secure the markers to your child's skin may cause irritation, and participation may not be suitable.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in a scientific journal to further knowledge in the field, and spark interest for researchers working with special populations. In any publication, information will be provided in such a way that your child cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

Your decision whether or not your child will participate will not prejudice your future relations with The University of New South Wales. If you decide that you would like your child to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

Please feel free to ask us any questions you might have. If you have any additional questions that you wish to ask after you have left, Dr Andrew McIntosh (9385 5348) and Ms Leanne Dwan (9385 5413) will be happy to answer them.
You will be given a copy of this form to keep.

APPENDIX G:

CONSENT FORM

The University of New South Wales
Participant Information and Consent Form
Quantitative Analysis of Upper Limb Range of Motion and
Functional Tests in Children
Approval No 8/04/01

You are making a decision whether or not you would like your child to participate. Your signature indicates that, having read the Participant Information Statement, you have decided to allow your child to take part in the study.

…………………………………………………
Name of Child (Research Participant)

…………………………………………………	…………………………………………………
Signature of Parent/Guardian of Research Participant	Signature of Witness
…………………………………………………	…………………………………………………
(Please PRINT name)	(Please PRINT name)
…………………………………………………	…………………………………………………
Date	Nature of Witness

…………………………………………………
Signature(s) of Investigator(s)

…………………………………………………
Please PRINT Name

APPENDIX H:

REVOCATION OF CONSENT FORM

The University of New South Wales
Participant Information and Consent Form
Quantitative Analysis of Upper Limb Range of Motion and Functional Tests in Children
Approval No 8/04/01

I hereby wish to **WITHDRAW** my consent for my child to participate in the research proposal described above and understand that such withdrawal **WILL NOT** jeopardise any treatment or my relationship with The University of New South Wales.

…………………………………………………..	……………………………………………………
Signature	Date

…………………………………………………..
Please PRINT Name

The section for Revocation of Consent should be forwarded to:

Dr Andrew McIntosh
School of Safety Science
University of New South Wales
Sydney NSW 2052

APPENDIX I:

EULER ANGLE CALCULATIONS MATLAB CODE – RIGHT SIDE

```
function [alpha_deg,beta_deg,gamma_deg] = eulerangleR(R)
beta = acos(R(3,3));
%---------------------------------- beta > 0 -----------------------------
if abs(sin(beta)) > 1.0e-10
  cos_alpha = R(1,3)/sin(beta);
  sin_alpha = R(2,3)/sin(beta);
  if cos_alpha >= 0
    alpha = asin(sin_alpha);           % Quadrant 1 or 4
  else
    if sin_alpha >= 0
      alpha = pi - asin(sin_alpha);                   % Quadrant 2
    else
        alpha = -pi - asin(sin_alpha);          % Quadrant 3
    end
  end
  cos_gamma  = -R(3,1)/sin(beta);
  sin_gamma  = R(3,2)/sin(beta);
  if cos_gamma >= 0
    gamma = asin(sin_gamma);
  else
    if  sin_gamma >= 0
      gamma = pi - asin(sin_gamma);
    else
      gamma = -pi - asin(sin_gamma);
    end
  end
else


%---------------------------------- beta < 1e-12 -------------------------
  s=1;
  if  R(3,3) < 0
    s=-1;
  end
  cos_alphgam = s*R(1,1);
  sin_alphgam = s*R(2,1);
  if cos_alphgam >= 0
    alpha = asin(sin_alphgam);
  else
    if sin_alphgam >= 0
      alpha = pi - asin(sin_alphgam);
    else
      alpha = -pi - asin(sin_alphgam);
    end
  end
```

```
  gamma = 0;
end
alpha_deg = -alpha*180/pi;
beta_deg = beta*180/pi;
gamma_deg = -gamma*180/pi;
```

APPENDIX J:

UPPER LIMB MODEL MATLAB CODE – RIGHT SIDE

```
{*-------------------------UPPER LIMB MODEL---------------------*}
{* OptionalPoints are markers used in static trial then removed *}
OptionalPoints(RGHA,RGHP,RACR,RINF,RMSP,RMCP)
{* Definition of local coordinate axes *}
{* Determine GH joint centre and segment corrections from static trial*}
{* Segment correction factors can be altered in parameter file *}
{* THORAX segment *}
        zthoraxa = (JUGN+C7)/2
        zthoraxb = (XIPH+T8)/2
        Thorax = [JUGN, zthoraxa-zthoraxb, JUGN-C7, zxy]
        Thorax = ROT(Thorax,1(Thorax),$ThoraxAPTilt)
        Thorax = ROT(Thorax,2(Thorax),$ThoraxLatTilt)
        T1 = 1(Thorax)
        T2 = 2(Thorax)
        T3 = 3(Thorax)
        OUTPUT(T1,T2,T3)
{*-----------------------Right Side of Body---------------------*}
{* Right SCAPULA segment *}
        RScapula = [RACR, RACR-RMSP, RINF-RMSP, xyz]
        RS1 = 1(RScapula)
        RS2 = 2(RScapula)
        RS3 = 3(RScapula)
{* Right CLAVICLE segment *}
        RClavicle = [JUGN, RACJ-JUGN, zthoraxa-zthoraxb, xyz]
{* Right HUMERUS segment *}
        If $Static == 1
                RGHJ = (RGHP+RGHA)/2
                $%RGHJ = RGHJ/RClavicle
                PARAM($%RGHJ)
        EndIf
        RGHJ = $%RGHJ*RClavicle
        REJC = (RLEP+RMEP)/2
        RHumerus = [RGHJ,RGHJ-REJC,RMEP-RLEP,zyx]
        RHumerus = ROT(RHumerus,3(RHumerus),$RHumerusRotation)
        RH1 = 1(RHumerus)
        RH2 = 2(RHumerus)
        RH3 = 3(RHumerus)
        OUTPUT(RGHJ,REJC,RH1,RH2,RH3)
{* Right FOREARM segment *}
        RWJC = (RULN + RRAD)/2
        RForearm = [REJC,REJC-RWJC,RMEP-RLEP,zyx]
        RForearm = ROT(RForearm,1(RForearm),$RElbRotation)
        OUTPUT(RWJC)
```

```
        RPronSup = [REJC,REJC-RULN,RULN-RRAD,zyx]
        RPronSup = ROT(RPronSup,3(RPronSup),$RForearmRotation)
        RForearm2 = [RWJC,REJC-RWJC,RULN-RRAD,zyx]
{* Right HAND segment *}
        RHand = [RWJC,RWJC-RMCP,RULN-RRAD,zyx]
        ROffset = 9.5 + ($RHandThickness/2)
        RSinTheta = ROffset/ABS(RWJC-RMCP)
        RTheta = ASIN(RSinTheta)
        RHand = ROT(RHand,1(RHand),RTheta)
        RHand = ROT(RHand,1(RHand),$RWristFlex)
        RHand = ROT(RHand,2(RHand),-$RWristDev)
        RHAN = {0,0,-ABS(RWJC-RMCP)}*COS(RTheta)*RHand
        OUTPUT(RHAN)



{*------------------------Kinematic Analysis--------------------*}
GlobalThorax = <Thorax,xyz>
RWrist = <RForearm2,RHand,xyz>
RWrist = <-1(RWrist),2(RWrist),3(RWrist)>
RElbowExt = <RForearm,RHumerus,xyz>
RSupinate = <RPronSup,RForearm,zxy>
RClavThor = <RClavicle,Thorax,zyx>
RClavThor = <-1(RClavThor),-2(RClavThor),-3(RClavThor)>
RScapThor = <RScapula,Thorax,zyx>
RScapThor = <-1(RScapThor),-2(RScapThor),-3(RScapThor)>
RScapClav = <RScapula,RClavicle,zyx>
RScapClav = <-1(RScapClav),-2(RScapClav),-3(RScapClav)>
RHumThor = <RHumerus,Thorax,xyz>
RHumThor = <1(RHumThor),2(RHumThor),3(RHumThor)>
OUTPUT(GlobalThorax,RClavThor)
OUTPUT(RScapThor,RScapClav)
OUTPUT(RElbowExt)
OUTPUT(RHumThor)
OUTPUT(RSupinate,RWrist)
{*------------------------------------------------------------*}
{*------------------------------------------------------------*}
```

APPENDIX K:

UPPER LIMB MODEL PARAMETER FILE

$Static = 0

$LHandThickness = 22
$RHandThickness = 22

$ThoraxAPTilt = -12.465
$ThoraxLatTilt = -2.4525

$LHumerusRotation = 6.961
$RHumerusRotation = 1.234

$LElbRotation = 8.704 {*elbow flexion*}
$RElbRotation = 5.12

$LForearmRotation = -104.46 {*pronation / supination*} {* add -ve of value on graphs to -90 *}
$RForearmRotation = -108.115

$LWristFlex = 0
$RWristFlex = 0

$LWristDev = 3.88
$RWristDev = 9.71

$%RGHJ = {134.876,-1.7956,-70.0515}
$%LGHJ = {-138.931,-0.0931324,-73.3706}
$%XIPH = {172.197,-12.6711,-60.8134}
$%JUGN = {129.599,8.44376,22.6903}

APPENDIX L:

ANATOMICAL MOVEMENTS PEAK JOINT ANGLE 2 WAY ANALYSIS OF VARIANCE STATISTICAL RESULTS – 6 REPEATED MOVEMENTS

Shoulder Elevation Maximum during Shoulder Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	121.445(a)	11	11.040	.200	.997
Intercept	5138237.501	1	5138237.501	93198.719	.000
Dom	14.162	1	14.162	.257	.613
Repeat	63.066	5	12.613	0.229	.950
Dom * Repeat	44.218	5	8.844	.160	.977
Error	12570.110	228	55.132		
Total	5150929.056	240			
Corrected Total	12691.555	239			

a R Squared = .010 (Adjusted R Squared = -.038)

Shoulder Elevation Maximum during Shoulder Abduction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	135.931(a)	11	12.357	0.274	0.99
Intercept	4922096.2	1	4922096	109032	0
Dom	36.185	1	36.185	0.802	0.372
Repeat	81.629	5	16.326	0.362	0.874
Dom * Repeat	18.118	5	3.624	0.08	0.995
Error	10292.718	228	45.144		
Total	4932524.8	240			
Corrected Total	10428.649	239			

a R Squared = .013 (Adjusted R Squared = -.035)

Shoulder Internal Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5176.765(a)	11	470.615	1.142	0.33
Intercept	417614.71	1	417615	1013.45	0
Dom	4469.218	1	4469.22	10.846	0.001
Repeat	427.945	5	85.589	0.208	0.959
Dom * Repeat	279.602	5	55.92	0.136	0.984
Error	93952.442	228	412.072		
Total	516743.91	240			
Corrected Total	99129.207	239			

a R Squared = .052 (Adjusted R Squared = .006)

Shoulder External Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	11980.232(a)	11	1089.112	1.151	0.323
Intercept	727729.13	1	727729.1	769.072	0
Dom	6999.588	1	6999.588	7.397	0.007
Repeat	2827.724	5	565.545	0.598	0.702
Dom * Repeat	2152.92	5	430.584	0.455	0.809
Error	215743.33	228	946.243		
Total	955452.69	240			
Corrected Total	227723.56	239			

a R Squared = .053 (Adjusted R Squared = .007)

Elbow Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	233.271(a)	11	21.206	0.552	0.866
Intercept	4523554.5	1	4523554	117841	0
Dom	223.513	1	223.513	5.823	0.017
Repeat	3.415	5	0.683	0.018	1
Dom * Repeat	6.343	5	1.269	0.033	0.999
Error	8752.233	228	38.387		
Total	4532540	240			
Corrected Total	8985.504	239			

a R Squared = .026 (Adjusted R Squared = -.021)

Elbow Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	136.019(a)	11	12.365	0.154	0.999
Intercept	239.081	1	239.081	2.977	0.086
Dom	68.459	1	68.459	0.852	0.357
Repeat	50.41	5	10.082	0.126	0.987
Dom * Repeat	17.15	5	3.43	0.043	0.999
Error	18309.749	228	80.306		
Total	18684.849	240			
Corrected Total	18445.768	239			

a R Squared = .007 (Adjusted R Squared = -.041)

Forearm Pronation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	884.637(a)	11	80.422	0.659	0.777
Intercept	1099438.6	1	1099439	9005.89	0
Dom	772.532	1	772.532	6.328	0.013
Repeat	99.125	5	19.825	0.162	0.976
Dom * Repeat	12.98	5	2.596	0.021	1
Error	27834.232	228	122.08		
Total	1128157.5	240			
Corrected Total	28718.868	239			

a R Squared = .031 (Adjusted R Squared = -.016)

Forearm Supination

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1209.425(a)	11	109.948	1.101	0.361
Intercept	1146218.4	1	1146218	11477.4	0
Dom	1187.839	1	1187.839	11.894	0.001
Repeat	14.353	5	2.871	0.029	1
Dom * Repeat	7.234	5	1.447	0.014	1
Error	22769.847	228	99.868		
Total	1170197.7	240			
Corrected Total	23979.272	239			

a R Squared = .050 (Adjusted R Squared = .005)

Wrist Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1009.700(a)	11	91.791	1.438	0.157
Intercept	1111007.5	1	1111007	17409.5	0
Dom	694.654	1	694.654	10.885	0.001
Repeat	277.769	5	55.554	0.871	0.502
Dom * Repeat	37.276	5	7.455	0.117	0.989
Error	14550.096	228	63.816		
Total	1126567.3	240			
Corrected Total	15559.796	239			

a R Squared = .065 (Adjusted R Squared = .020)

Wrist Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	252.203(a)	11	22.928	0.364	0.969
Intercept	578818.32	1	578818.3	9189.77	0
Dom	8.71	1	8.71	0.138	0.71
Repeat	198.641	5	39.728	0.631	0.676
Dom * Repeat	44.852	5	8.97	0.142	0.982
Error	14360.599	228	62.985		
Total	593431.12	240			
Corrected Total	14612.802	239			

a R Squared = .017 (Adjusted R Squared = -.030)

Radial Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	462.188(a)	11	42.017	1.014	0.435
Intercept	108418.24	1	108418	2615.52	0
Dom	410.804	1	410.804	9.91	0.002
Repeat	37.556	5	7.511	0.181	0.969
Dom * Repeat	13.649	5	2.73	0.066	0.997
Error	9202.321	222	41.452		
Total	118496.81	234			
Corrected Total	9664.509	233			

a R Squared = .048 (Adjusted R Squared = .001)

Ulnar Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	239.808(a)	11	21.801	0.489	0.909
Intercept	82050.099	1	82050.1	1842.25	0
Dom	201.528	1	201.528	4.525	0.035
Repeat	6.208	5	1.242	0.028	1
Dom * Repeat	31.521	5	6.304	0.142	0.982
Error	9887.46	222	44.538		
Total	92022.81	234			
Corrected Total	10127.267	233			

a R Squared = .024 (Adjusted R Squared = -.025)

APPENDIX M:

HAND TO MOUTH MOVEMENT PEAK JOINT ANGLE 2 WAY ANALYSIS OF VARIANCE STATISTICAL RESULTS

Shoulder Joint Horizontal Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	330.254(a)	5	66.051	0.53	0.753
Intercept	972136.81	1	972137	7803.02	0
Dominance	316.225	1	316.225	2.538	0.114
Repeat	1.391	2	0.696	0.006	0.994
Dominance * Repeat	12.637	2	6.318	0.051	0.951
Error	14202.66	114	124.585		
Total	986669.72	120			
Corrected Total	14532.913	119			

a R Squared = .023 (Adjusted R Squared = -.020)

Shoulder Joint Horizontal Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	844.344(a)	5	168.869	0.194	0.964
Intercept	164705.04	1	164705.04	189.479	0
Dominance	61.118	1	61.118	0.07	0.791
Repeat	672.148	2	336.074	0.387	0.68
Dominance * Repeat	111.077	2	55.539	0.064	0.938
Error	99094.89	114	869.253		
Total	264644.27	120			
Corrected Total	99939.233	119			

a R Squared = .008 (Adjusted R Squared = -.035)

Shoulder Joint Elevation Maximum

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	297.499(a)	5	59.5	0.549	0.739
Intercept	230391.54	1	230391.54	2125.63	0
Dominance	292.094	1	292.094	2.695	0.103
Repeat	0.129	2	0.065	0.001	0.999
Dominance * Repeat	5.275	2	2.638	0.024	0.976
Error	12356.16	114	108.387		
Total	243045.2	120			
Corrected Total	12653.659	119			

a R Squared = .024 (Adjusted R Squared = -.019)

Shoulder Internal Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2316.914(a)	5	463.383	0.508	0.77
Intercept	424207.86	1	424207.86	464.738	0
Dominance	1955.442	1	1955.442	2.142	0.146
Repeat	321.887	2	160.943	0.176	0.839
Dominance * Repeat	39.585	2	19.792	0.022	0.979
Error	104058	114	912.789		
Total	530582.77	120			
Corrected Total	106374.91	119			

a R Squared = .022 (Adjusted R Squared = -.021)

Shoulder External Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1805.066(a)	5	361.013	1.211	0.308
Intercept	441335.5	1	441335.5	1480.74	0
Dominance	1637.476	1	1637.476	5.494	0.021
Repeat	44.22	2	22.11	0.074	0.929
Dominance * Repeat	123.37	2	61.685	0.207	0.813
Error	33977.822	114	298.051		
Total	477118.39	120			
Corrected Total	35782.888	119			

a R Squared = .050 (Adjusted R Squared = .009)

Elbow Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	191.862(a)	5	38.372	0.732	0.601
Intercept	2199305	1	2199305	41943.3	0
Dominance	172.968	1	172.968	3.299	0.072
Repeat	1.239	2	0.619	0.012	0.988
Dominance * Repeat	17.655	2	8.828	0.168	0.845
Error	5977.617	114	52.435		
Total	2205474.4	120			
Corrected Total	6169.479	119			

a R Squared = .031 (Adjusted R Squared = -.011)

Elbow Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	623.265(a)	5	124.653	1.65	0.152
Intercept	38139.084	1	38139.084	504.864	0
Dominance	544.258	1	544.258	7.205	0.008
Repeat	61.13	2	30.565	0.405	0.668
Dominance * Repeat	17.877	2	8.938	0.118	0.889
Error	8611.937	114	75.543		
Total	47374.286	120			
Corrected Total	9235.202	119			

a R Squared = .067 (Adjusted R Squared = .027)

Forearm Pronation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	854.407(a)	5	170.881	0.341	0.887
Intercept	2217.166	1	2217.166	4.422	0.038
Dominance	26.33	1	26.33	0.053	0.819
Repeat	236.875	2	118.437	0.236	0.79
Dominance * Repeat	591.203	2	295.601	0.59	0.556
Error	57157.746	114	501.384		
Total	60229.319	120			
Corrected Total	58012.153	119			

a R Squared = .015 (Adjusted R Squared = -.028)

Forearm Supination

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1327.555(a)	5	265.511	1.566	0.175
Intercept	242262.56	1	242262.56	1428.97	0
Dominance	308.289	1	308.289	1.818	0.18
Repeat	976.681	2	488.34	2.88	0.06
Dominance * Repeat	42.585	2	21.293	0.126	0.882
Error	19327.114	114	169.536		
Total	262917.23	120			
Corrected Total	20654.669	119			

a R Squared = .064 (Adjusted R Squared = .023)

Wrist Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	98.683(a)	5	19.737	0.21	0.957
Intercept	44503.697	1	44503.697	474.53	0
Dominance	48.057	1	48.057	0.512	0.476
Repeat	17.444	2	8.722	0.093	0.911
Dominance * Repeat	33.182	2	16.591	0.177	0.838
Error	10691.463	114	93.785		
Total	55293.843	120			
Corrected Total	10790.146	119			

a R Squared = .009 (Adjusted R Squared = -.034)

Wrist Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	803.659(a)	5	160.732	1.156	0.335
Intercept	5538.469	1	5538.469	39.847	0
Dominance	306.496	1	306.496	2.205	0.14
Repeat	364.058	2	182.029	1.31	0.274
Dominance * Repeat	133.104	2	66.552	0.479	0.621
Error	15845.397	114	138.995		
Total	22187.524	120			
Corrected Total	16649.055	119			

a R Squared = .048 (Adjusted R Squared = .007)

Radial Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	70.906(a)	5	14.181	0.251	0.939
Intercept	16426.566	1	16426.566	290.4	0
Dominance	44.153	1	44.153	0.781	0.379
Repeat	6.155	2	3.078	0.054	0.947
Dominance * Repeat	20.598	2	10.299	0.182	0.834
Error	6448.443	114	56.565		
Total	22945.915	120			
Corrected Total	6519.349	119			

a R Squared = .011 (Adjusted R Squared = -.033)

Ulnar Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	192.153(a)	5	38.431	1.049	0.392
Intercept	10169.868	1	10169.868	277.702	0
Dominance	84.924	1	84.924	2.319	0.131
Repeat	47.5	2	23.75	0.649	0.525
Dominance * Repeat	59.729	2	29.864	0.815	0.445
Error	4174.854	114	36.622		
Total	14536.875	120			
Corrected Total	4367.006	119			

a R Squared = .044 (Adjusted R Squared = .002)

APPENDIX N:

HAND TO MOUTH MOVEMENT TIMING OF PEAK JOINT ANGLE 2 WAY ANALYSIS OF VARIANCE STATISTICAL RESULTS

Shoulder Joint Horizontal Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.007(a)	5	0.001	0.212	0.957
Intercept	32.178	1	32.178	4719.91	0
Dominance	0.004	1	0.004	0.565	0.454
Repeat	0.002	2	0.001	0.155	0.857
Dominance * Repeat	0.001	2	0.001	0.093	0.911
Error	0.777	114	0.007		
Total	32.963	120			
Corrected Total	0.784	119			

a R Squared = .009 (Adjusted R Squared = -.034)

Shoulder Joint Horizontal Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.850(a)	5	0.57	2.502	0.034
Intercept	30.09	1	30.09	132.075	0
Dominance	0.45	1	0.45	1.976	0.163
Repeat	0.573	2	0.287	1.258	0.288
Dominance * Repeat	1.826	2	0.913	4.008	0.021
Error	25.972	114	0.228		
Total	58.912	120			
Corrected Total	28.822	119			

a R Squared = .099 (Adjusted R Squared = .059)

Shoulder Joint Elevation Maximum

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.052(a)	5	0.01	1.021	0.409
Intercept	29.077	1	29.077	2854.84	0
Dominance	0.004	1	0.004	0.39	0.534
Repeat	0.012	2	0.006	0.6	0.551
Dominance * Repeat	0.036	2	0.018	1.757	0.177
Error	1.161	114	0.01		
Total	30.29	120			
Corrected Total	1.213	119			

a R Squared = .043 (Adjusted R Squared = .001)

Shoulder Internal Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.728(a)	5	0.146	0.599	0.701
Intercept	25.845	1	25.845	106.404	0
Dominance	0.088	1	0.088	0.362	0.548
Repeat	0.432	2	0.216	0.89	0.413
Dominance * Repeat	0.207	2	0.104	0.427	0.654
Error	27.69	114	0.243		
Total	54.262	120			
Corrected Total	28.417	119			

a R Squared = .026 (Adjusted R Squared = -.017)

Shoulder External Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.190(a)	5	0.038	0.855	0.514
Intercept	32.044	1	32.044	719.55	0
Dominance	0.106	1	0.106	2.385	0.125
Repeat	0.027	2	0.014	0.308	0.735
Dominance * Repeat	0.057	2	0.028	0.636	0.531
Error	5.077	114	0.045		
Total	37.311	120			
Corrected Total	5.267	119			

a R Squared = .036 (Adjusted R Squared = -.006)

Elbow Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.023(a)	5	0.005	1.019	0.41
Intercept	26.999	1	26.999	6099.67	0
Dominance	0.011	1	0.011	2.447	0.121
Repeat	0.007	2	0.004	0.8	0.452
Dominance * Repeat	0.005	2	0.002	0.524	0.594
Error	0.505	114	0.004		
Total	27.526	120			
Corrected Total	0.527	119			

a R Squared = .043 (Adjusted R Squared = .001)

Elbow Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.265(a)	5	0.853	4.145	0.002
Intercept	35.165	1	35.165	170.872	0
Dominance	0.001	1	0.001	0.006	0.936
Repeat	3.05	2	1.525	7.411	0.001
Dominance * Repeat	1.213	2	0.607	2.947	0.056
Error	23.461	114	0.206		
Total	62.891	120			
Corrected Total	27.726	119			

a R Squared = .154 (Adjusted R Squared = .117)

Forearm Pronation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.313(a)	5	0.063	0.352	0.88
Intercept	41.501	1	41.501	233.576	0
Dominance	0.021	1	0.021	0.116	0.734
Repeat	0.285	2	0.142	0.801	0.452
Dominance * Repeat	0.008	2	0.004	0.022	0.978
Error	20.255	114	0.178		
Total	62.069	120			
Corrected Total	20.568	119			

a R Squared = .015 (Adjusted R Squared = -.028)

Forearm Supination

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.053(a)	5	0.011	0.195	0.964
Intercept	21.455	1	21.455	395.588	0
Dominance	0	1	0	0.007	0.931
Repeat	0.007	2	0.003	0.061	0.941
Dominance * Repeat	0.046	2	0.023	0.423	0.656
Error	6.183	114	0.054		
Total	27.69	120			
Corrected Total	6.236	119			

a R Squared = .008 (Adjusted R Squared = -.035)

Wrist Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.629(a)	5	0.126	0.744	0.592
Intercept	33.899	1	33.899	200.586	0
Dominance	0.056	1	0.056	0.333	0.565
Repeat	0.24	2	0.12	0.711	0.493
Dominance * Repeat	0.332	2	0.166	0.982	0.378
Error	19.266	114	0.169		
Total	53.794	120			
Corrected Total	19.895	119			

a R Squared = .032 (Adjusted R Squared = -.011)

Wrist Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.270(a)	5	0.054	0.705	0.621
Intercept	29.621	1	29.621	386.365	0
Dominance	0.068	1	0.068	0.889	0.348
Repeat	0.198	2	0.099	1.29	0.279
Dominance * Repeat	0.004	2	0.002	0.027	0.973
Error	8.74	114	0.077		
Total	38.631	120			
Corrected Total	9.01	119			

a R Squared = .030 (Adjusted R Squared = -.013)

Radial Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.047(a)	5	0.009	0.325	0.897
Intercept	34.68	1	34.68	1202.78	0
Dominance	0.035	1	0.035	1.215	0.273
Repeat	0.001	2	0	0.016	0.984
Dominance * Repeat	0.011	2	0.005	0.189	0.828
Error	3.287	114	0.029		
Total	38.013	120			
Corrected Total	3.334	119			

a R Squared = .014 (Adjusted R Squared = -.029)

Ulnar Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.163(a)	5	0.233	1.278	0.278
Intercept	20.933	1	20.933	114.943	0
Dominance	0.528	1	0.528	2.899	0.091
Repeat	0.138	2	0.069	0.378	0.686
Dominance * Repeat	0.498	2	0.249	1.366	0.259
Error	20.762	114	0.182		
Total	42.858	120			
Corrected Total	21.925	119			

a R Squared = .053 (Adjusted R Squared = .012)

APPENDIX O:

HAND OVER HEAD MOVEMENT PEAK JOINT ANGLE 2 WAY ANALYSIS OF VARIANCE STATISTICAL RESULTS

Shoulder Joint Horizontal Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	580.356(a)	5	116.071	0.986	0.429
Intercept	528890.62	1	528891	4495.09	0
Dominance	521.625	1	521.625	4.433	0.037
Repeat	1.095	2	0.547	0.005	0.995
Dominance * Repeat	57.636	2	28.818	0.245	0.783
Error	13413.204	114	117.66		
Total	542884.18	120			
Corrected Total	13993.56	119			

a R Squared = .041 (Adjusted R Squared = -.001)

Shoulder Joint Horizontal Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1536.727(a)	5	307.345	1.125	0.351
Intercept	437460.35	1	437460.3	1600.85	0
Dominance	1453.387	1	1453.387	5.319	0.023
Repeat	7.051	2	3.526	0.013	0.987
Dominance * Repeat	76.288	2	38.144	0.14	0.87
Error	31152.546	114	273.268		
Total	470149.62	120			
Corrected Total	32689.273	119			

a R Squared = .047 (Adjusted R Squared = .005)

Shoulder Joint Elevation Maximum

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	155.918(a)	5	31.184	0.248	0.94
Intercept	1768091.5	1	1768091	14034.2	0
Dominance	6.907	1	6.907	0.055	0.815
Repeat	126	2	63	0.5	0.608
Dominance * Repeat	23.011	2	11.506	0.091	0.913
Error	14362.234	114	125.985		
Total	1782609.6	120			
Corrected Total	14518.153	119			

a R Squared = .011 (Adjusted R Squared = -.033)

Shoulder Internal Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	180.460(a)	5	36.092	0.16	0.977
Intercept	639884.48	1	639884	2829.42	0
Dominance	4.836	1	4.836	0.021	0.884
Repeat	72.663	2	36.331	0.161	0.852
Dominance * Repeat	102.961	2	51.48	0.228	0.797
Error	25781.519	114	226.154		
Total	665846.46	120			
Corrected Total	25961.978	119			

a R Squared = .007 (Adjusted R Squared = -.037)

Shoulder External Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	279.746(a)	5	55.949	0.425	0.83
Intercept	921801.03	1	921801	7006.83	0
Dominance	226.82	1	226.82	1.724	0.192
Repeat	13.467	2	6.733	0.051	0.95
Dominance * Repeat	39.46	2	19.73	0.15	0.861
Error	14997.546	114	131.557		
Total	937078.32	120			
Corrected Total	15277.293	119			

a R Squared = .018 (Adjusted R Squared = -.025)

Elbow Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	255.420(a)	5	51.084	0.978	0.435
Intercept	2409123.9	1	2409124	46102.4	0
Dominance	248.63	1	248.63	4.758	0.031
Repeat	0.155	2	0.078	0.001	0.999
Dominance * Repeat	6.634	2	3.317	0.063	0.939
Error	5957.178	114	52.256		
Total	2415336.5	120			
Corrected Total	6212.598	119			

a R Squared = .041 (Adjusted R Squared = -.001)

Elbow Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	359.633(a)	5	71.927	0.862	0.509
Intercept	61107.825	1	61107.83	732.325	0
Dominance	230.575	1	230.575	2.763	0.099
Repeat	35.575	2	17.788	0.213	0.808
Dominance * Repeat	93.483	2	46.741	0.56	0.573
Error	9512.574	114	83.444		
Total	70980.032	120			
Corrected Total	9872.206	119			

a R Squared = .036 (Adjusted R Squared = -.006)

Forearm Pronation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	887.229(a)	5	177.446	0.455	0.809
Intercept	97218.223	1	97218.2	249.449	0
Dominance	437.466	1	437.466	1.122	0.292
Repeat	142.961	2	71.48	0.183	0.833
Dominance * Repeat	306.802	2	153.401	0.394	0.676
Error	44429.437	114	389.732		
Total	142534.89	120			
Corrected Total	45316.666	119			

a R Squared = .020 (Adjusted R Squared = -.023)

Forearm Supination

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1232.037(a)	5	246.407	1.812	0.116
Intercept	442877.22	1	442877.2	3256.75	0
Dominance	1134.921	1	1134.921	8.346	0.005
Repeat	50.986	2	25.493	0.187	0.829
Dominance * Repeat	46.13	2	23.065	0.17	0.844
Error	15502.584	114	135.988		
Total	459611.84	120			
Corrected Total	16734.621	119			

a R Squared = .074 (Adjusted R Squared = .033)

Wrist Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1711.846(a)	5	342.369	1.278	0.278
Intercept	170724.49	1	170724	637.435	0
Dominance	1277.073	1	1277.07	4.768	0.031
Repeat	89.872	2	44.936	0.168	0.846
Dominance * Repeat	344.901	2	172.45	0.644	0.527
Error	30532.684	114	267.831		
Total	202969.02	120			
Corrected Total	32244.531	119			

a R Squared = .053 (Adjusted R Squared = .012)

Wrist Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	819.306(a)	5	163.861	0.292	0.916
Intercept	55856.812	1	55856.81	99.627	0
Dominance	639.039	1	639.039	1.14	0.288
Repeat	107.977	2	53.988	0.096	0.908
Dominance * Repeat	72.29	2	36.145	0.064	0.938
Error	63915.011	114	560.658		
Total	120591.13	120			
Corrected Total	64734.317	119			

a R Squared = .013 (Adjusted R Squared = -.031)

Radial Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	88.632(a)	5	17.726	0.244	0.942
Intercept	42677.917	1	42677.9	587.741	0
Dominance	25.337	1	25.337	0.349	0.556
Repeat	10.606	2	5.303	0.073	0.93
Dominance * Repeat	52.689	2	26.344	0.363	0.697
Error	8277.938	114	72.613		
Total	51044.487	120			
Corrected Total	8366.57	119			

a R Squared = .011 (Adjusted R Squared = -.033)

Ulnar Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38.841(a)	5	7.768	0.245	0.942
Intercept	16682.143	1	16682.14	526.254	0
Dominance	0.191	1	0.191	0.006	0.938
Repeat	0.678	2	0.339	0.011	0.989
Dominance * Repeat	37.972	2	18.986	0.599	0.551
Error	3613.776	114	31.7		
Total	20334.76	120			
Corrected Total	3652.617	119			

a R Squared = .011 (Adjusted R Squared = -.033)

APPENDIX P:

HAND OVER HEAD MOVEMENT TIMING OF PEAK JOINT ANGLE 2 WAY ANALYSIS OF VARIANCE STATISTICAL RESULTS

Shoulder Joint Horizontal Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.242(a)	5	0.048	1.128	0.349
Intercept	15.401	1	15.401	359.373	0
Dominance	0.039	1	0.039	0.916	0.341
Repeat	0.18	2	0.09	2.096	0.128
Dominance * Repeat	0.023	2	0.011	0.267	0.766
Error	4.886	114	0.043		
Total	20.529	120			
Corrected Total	5.127	119			

a R Squared = .047 (Adjusted R Squared = .005)

Shoulder Joint Horizontal Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.248(a)	5	0.25	1.366	0.242
Intercept	56.348	1	56.348	308.569	0
Dominance	0.141	1	0.141	0.771	0.382
Repeat	0.997	2	0.499	2.73	0.069
Dominance * Repeat	0.11	2	0.055	0.3	0.741
Error	20.818	114	0.183		
Total	78.413	120			
Corrected Total	22.065	119			

a R Squared = .057 (Adjusted R Squared = .015)

Shoulder Joint Elevation Maximum

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.013(a)	5	0.003	0.468	0.799
Intercept	35.872	1	35.872	6662.22	0
Dominance	0	1	0	0.019	0.891
Repeat	0.006	2	0.003	0.574	0.565
Dominance * Repeat	0.006	2	0.003	0.587	0.557
Error	0.614	114	0.005		
Total	36.499	120			
Corrected Total	0.626	119			

a R Squared = .020 (Adjusted R Squared = -.023)

Shoulder Internal Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.689(a)	5	0.538	2.481	0.036
Intercept	38.59	1	38.59	178.035	0
Dominance	0.065	1	0.065	0.299	0.585
Repeat	1.283	2	0.642	2.96	0.056
Dominance * Repeat	1.341	2	0.67	3.093	0.049
Error	24.71	114	0.217		
Total	65.989	120			
Corrected Total	27.399	119			

a R Squared = .098 (Adjusted R Squared = .059)

Shoulder External Rotation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.045(a)	5	0.009	0.641	0.669
Intercept	49.331	1	49.331	3532.81	0
Dominance	0.009	1	0.009	0.645	0.423
Repeat	0.022	2	0.011	0.804	0.45
Dominance * Repeat	0.013	2	0.007	0.476	0.622
Error	1.592	114	0.014		
Total	50.968	120			
Corrected Total	1.637	119			

a R Squared = .027 (Adjusted R Squared = -.015)

Elbow Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.022(a)	5	0.004	0.672	0.646
Intercept	59.052	1	59.052	8856.33	0
Dominance	0	1	0	0.018	0.894
Repeat	0.022	2	0.011	1.623	0.202
Dominance * Repeat	0.001	2	0	0.048	0.954
Error	0.76	114	0.007		
Total	59.835	120			
Corrected Total	0.783	119			

a R Squared = .029 (Adjusted R Squared = -.014)

Elbow Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.491(a)	5	0.298	1.303	0.268
Intercept	21.811	1	21.811	95.286	0
Dominance	0.151	1	0.151	0.661	0.418
Repeat	0.129	2	0.065	0.283	0.754
Dominance * Repeat	1.21	2	0.605	2.644	0.075
Error	26.095	114	0.229		
Total	49.397	120			
Corrected Total	27.586	119			

a R Squared = .054 (Adjusted R Squared = .013)

Forearm Pronation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.122(a)	5	0.024	0.37	0.868
Intercept	61.361	1	61.361	931.912	0
Dominance	0.003	1	0.003	0.047	0.829
Repeat	0.005	2	0.002	0.036	0.964
Dominance * Repeat	0.114	2	0.057	0.864	0.424
Error	7.506	114	0.066		
Total	68.989	120			
Corrected Total	7.628	119			

a R Squared = .016 (Adjusted R Squared = -.027)

Forearm Supination

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.053(a)	5	0.011	0.222	0.952
Intercept	22.629	1	22.629	472.944	0
Dominance	0.011	1	0.011	0.23	0.632
Repeat	0.033	2	0.016	0.342	0.711
Dominance * Repeat	0.009	2	0.005	0.099	0.906
Error	5.455	114	0.048		
Total	28.137	120			
Corrected Total	5.508	119			

a R Squared = .010 (Adjusted R Squared = -.034)

Wrist Flexion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.614(a)	5	0.123	1.193	0.317
Intercept	34.723	1	34.723	337.368	0
Dominance	0.291	1	0.291	2.828	0.095
Repeat	0.224	2	0.112	1.09	0.34
Dominance * Repeat	0.098	2	0.049	0.478	0.621
Error	11.733	114	0.103		
Total	47.07	120			
Corrected Total	12.347	119			

a R Squared = .050 (Adjusted R Squared = .008)

Wrist Extension

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.317(a)	5	0.063	0.96	0.445
Intercept	52.881	1	52.881	800.672	0
Dominance	0.117	1	0.117	1.765	0.187
Repeat	0.183	2	0.092	1.388	0.254
Dominance * Repeat	0.017	2	0.009	0.13	0.878
Error	7.529	114	0.066		
Total	60.727	120			
Corrected Total	7.846	119			

a R Squared = .040 (Adjusted R Squared = -.002)

Radial Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.028(a)	5	0.006	0.378	0.863
Intercept	57.838	1	57.838	3888.97	0
Dominance	0.006	1	0.006	0.405	0.526
Repeat	0.016	2	0.008	0.529	0.591
Dominance * Repeat	0.006	2	0.003	0.213	0.809
Error	1.695	114	0.015		
Total	59.562	120			
Corrected Total	1.724	119			

a R Squared = .016 (Adjusted R Squared = -.027)

Ulnar Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.417(a)	5	0.083	0.586	0.711
Intercept	15.885	1	15.885	111.606	0
Dominance	0.03	1	0.03	0.211	0.647
Repeat	0.364	2	0.182	1.28	0.282
Dominance * Repeat	0.023	2	0.011	0.08	0.923
Error	16.226	114	0.142		
Total	32.528	120			
Corrected Total	16.643	119			

a R Squared = .025 (Adjusted R Squared = -.018)