Three dimensional movement analysis of the upper limb during activities of daily living, in children with obstetric brachial plexus palsy: comparison with typically developing children

AUTHOR(S)

Julia Mahon

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List of abbreviations

2D:	Two dimensional
3D:	Three dimensional
3D-ULMA:	Three dimensional upper limb motion analysis
AC:	Acromion cluster
ACS:	Anatomical coordinate system
ADL:	Activities of daily living
AM:	Acromion method
AMS:	Active movement scale
A/P:	Anterior/Posterior
AR:	Axial rotation
B&A:	Bland and Altman
CI:	Confidence intervals
CRC:	Central Remedial Clinic
DC:	Double calibration
EM:	Humeral medial epicondyle
EMG:	Electromyography
F/E:	Flexion/Extension
GCS:	Global coordinate system
GH:	Glenohumeral
HCP:	Hemiplegic cerebral palsy
ICC:	Intraclass correlation coefficient
ICF:	International classification of functioning, disability and health
ISB:	International Society of Biomechanics
LCS:	Local coordinate system
LED:	Light emitting diode
LM:	Humeral lateral epicondyle
LOM:	Limits of agreement
MDC:	Minimal detectable change

M/L:	Medial/Lateral
MRI:	Magnetic resonance imaging
NC:	Narakas Classification
OBPP:	Obstetric brachial plexus palsy
OPS:	Optotrak probing system
OR:	Odds ratio
P/R:	Protraction/Retraction
P/S:	Pronation/Supination
POE:	Plane of Elevation
PM:	Pseudomeningocele
PTA:	Point of task achievement
QOL:	Quality of life
RMSE:	Root mean square error
ROM:	Range of motion
RS:	Radial Styloid
SHEAR:	Scapula hypoplasia elevation and rotation
SHR:	Scapulohumeral rhythm
S.SC	Sternoclavicular
S.AC	Acromioclavicular
SC:	Single calibration
SD:	Standard deviation
SEM:	Standard error of measurement
SL:	Scapular locator
ST:	Scapulothoracic
TDC:	Typically developing children
TH:	Thoracohumeral
TTS:	Toronto test score
US:	Ulnar styloid

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Summary

Residual shoulder dysfunction and deformity impacts on functional performance in children with obstetric brachial plexus palsy (OBPP). Clinical understanding of dynamic movement patterns of the upper limb is difficult with observation alone. Three-dimensional gait analysis has contributed significantly to understanding and management of gait dysfunction. In contrast, upper limb kinematic analysis is in its infancy due to the inherent challenges it presents. The aims of this study were to: determine test-retest reliability of three-dimensional upper limb motion analysis (3D-ULMA) in children with OBPP while performing functional tasks; determine its ability to identify discriminative upper limb spatiotemporal and kinematic characteristics between children with OBPP and typically developing children (TDC).

The test-retest reliability study of ten children with OBPP (mean 10 years, range 7-15 years, Narakas classification I-III) demonstrated inconsistent reliability. Despite this finding, as the first study to provide details of measurement error in this population it allowed more accurate interpretation of the variables analysed in the case-control study. The case-control study, involving 11 participants with OBPP and 10 TDC (mean 9 years 9 months, range 6-15 years), found that 3D-ULMA could characterise kinematic differences between children with OBPP and TDC while performing functional tasks. Children with OBPP demonstrated reduced external rotation in all tasks combined with reduced active control of internal rotation. Reduced glenohumeral joint motion was the main contributor to impaired function and altered scapulohumeral rhythm in children with OBPP. This finding emphasises the importance of maintaining glenohumeral joint integrity through available therapeutic and surgical interventions. A significant reduction in forearm supination was also found which concurred with previous research.

Future kinematic studies in children with OBPP should subgroup according to age and severity of involvement; examine timing of scapulothoracic joint motion and analyse thorax and neck motion.

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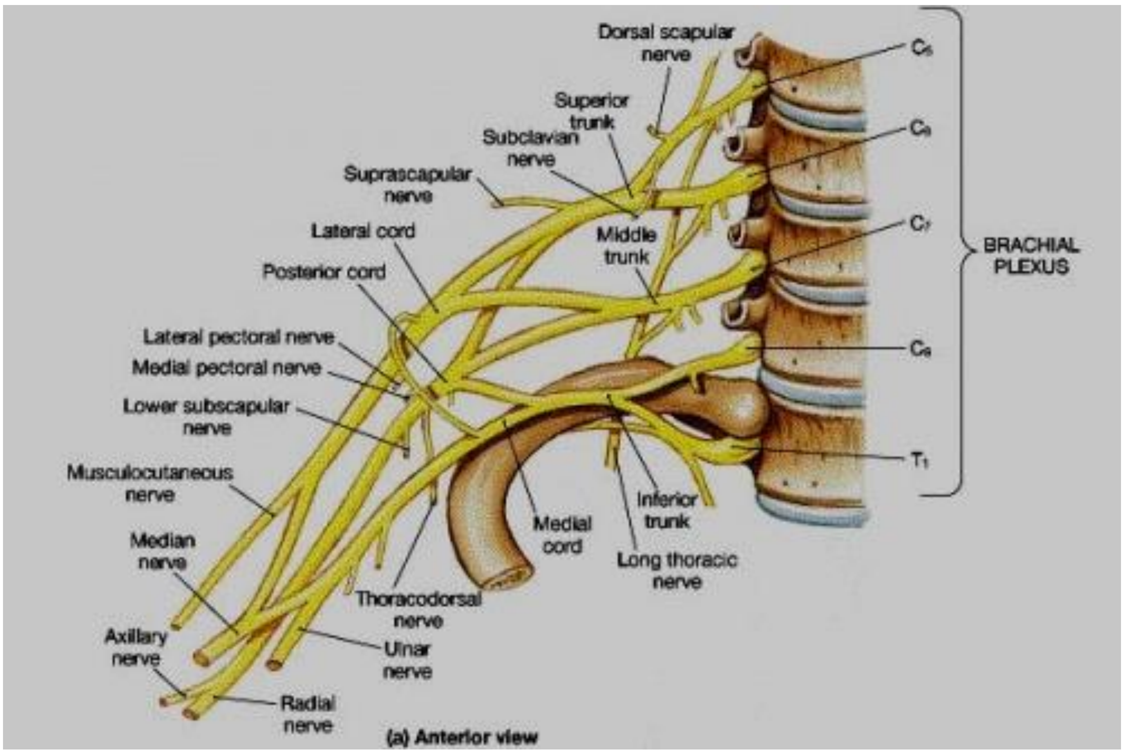
Chapter 1 Introduction and Literature Review

1.1 Introduction

This chapter provides an overview of obstetric brachial plexus palsy (OBPP), its incidence, presentation and management. It evaluates current objective assessments of OBPP used in clinical practice, three dimensional upper limb motion analysis (3D-ULMA) in OBPP and finally presents the aims of this research study.

1.2 Brachial plexus

The brachial plexus is a network of nerves that supply the upper limb. It starts at the root of the neck entering the arm through the axilla. It originates from anterior divisions of the cervical spinal nerves of C5, 6, 7, 8 and the first thoracic nerve, T1. For ease of description it is divided into five parts: roots, trunks, divisions, cords and branches (Figure 1.1).



Courtesy of RahulGladwin.com/images

Figure 1.1: Diagram of the Brachial Plexus

The branches form the final nerves that supply all the muscles and skin of the upper limb. The major branches are presented in Table 1.1.

Table 1.1: Major branches of the brachial plexus

Name	Nerve Root	Muscles Innervated
Musculocutaneous	C5, 6, 7	Biceps, Brachialis, Coracobrachialis
Axillary	C5, 6	Deltoid, Teres minor, Long head of triceps
Median	C6, 8 & T1	Most of forearm flexors, Thenar muscles, Two lateral lumbricals
Radial	C5-8 & T1	Triceps, Extensor muscles of posterior forearm
Ulnar	C8, T1	Muscles of hand (apart from the thenar muscles and two lateral lumbricals), Flexor carpi ulnaris, Medial half of flexor digitorum profundus

In addition to the five major branches, minor branches extend from all sections of the plexus to supply various aspects of the upper limb. These are presented in Table 1.2.

Table 1.2: Minor Branches of the brachial plexus

Origin	Minor Branches
Roots	Dorsal scapular; Long thoracic nerve
Trunks	Suprascapular; Nerve to Subclavius
Lateral Cord	Lateral pectoral
Medial Cord	Medial pectoral; Medial cutaneous nerve of arm and forearm
Posterior Cord	Subscapular; Thoracodorsal; Inferior subscapular

1.3 Causes of OBPP

The brachial plexus can be injured by any force that alters the anatomical relationship between neck, shoulder girdle and arm. Most, though not all, OBPP injuries are due to a longitudinal stretch of the spinal nerves extending from the spinal cord to the clavicle. This is believed to be caused by lateral traction of the brachial plexus at the time of delivery. While associated with shoulder dystocia this was not always present (Evans-Jones et al., 2003). Shoulder dystocia has been defined as the requirement of additional obstetric manoeuvres when gentle downward traction has failed to deliver the shoulder (Hansen and Chauhan, 2014). OBPP can occur with caesarean section suggesting a possible intrauterine pathogenesis (Walsh et al., 2011).

1.4 Incidence of OBPP

Studies report varying incidences of OBPP in the literature, with between 0.1-6.3 per 1000 live births reported in a recent literature review (Chauhan et al., 2014). This was attributed to different reporting and sampling methods. For example, some studies were in specialist referral centres rather than based on the general population. A study based on the latter (Evans-Jones et al., 2003) in the United Kingdom and Republic of Ireland reported a rate of 0.42 per 1000 live births. This was lower than 2.9 per 1000 live births reported from a prospective population based study over a two year period in western Sweden (Lagerkvist et al., 2010). The United States incidence rate was reported to be 1.5 per 1000 live births (Foad et al., 2008, Chauhan et al., 2014). An Irish study has shown that, despite training in the management of shoulder dystocia and an increasing caesarean section rate, the incidence of OBPP has not significantly changed in the past 10 years. They found that 1.7 per 1000 live births was reported for the period 2004-2008 compared with 1.5 per 1000 live births during the epoch 1994-1998 (Walsh et al., 2011).

Despite improvements in medical care and awareness of potential risk factors for OBPP the incidence has not significantly changed over the past ten years. With permanent disability a potential consequence of injury, enhancing the understanding of clinical presentation is crucial in ensuring optimal management.

1.5 Risk factors

Although there are several well recognised risk factors associated with OBPP (Table 1.3) not all cases have either a risk factor or a clear cause (Evans-Jones et al., 2003, Andersen et al., 2006, Doumouchtsis and Arulkumaran, 2009, Foad et al., 2009, Walsh et al., 2011). In addition, the ability to modify risk factors was not always possible with the need to manage every case based on clinical presentation identified as crucial (Zuarez-Easton et al., 2014).

Table 1.3: Risk Factors for OBPP

Risk Factors for OBPP	Adjusted Odds ratio (95% Confidence Interval)
Shoulder dystocia	38.5 (33.5 - 44.5)
Breech presentation	8.8 (7-11)
Macrosomia	8.7 (7.9-9.6)
Assisted vaginal delivery	3.4 (3.1-3.8)
Prolonged second stage of labor	1.3 (1.2-1.35)
Diabetes Mellitus	2.4 (1.7-3.5)
Prolonged labor	1.5 (1.2-1.8)
Induction of labor	1.1 (1-1.3)

Adapted from (Margareta et al., 2005)

1.5.1 Macrosomia

Macrosomia has been identified as a strong predictor of OBPP (Andersen et al., 2006, Foad et al., 2008). This identified a newborn who is significantly larger than typical newborns and is classified as any baby >4kg. However, due to the inaccuracy in predicting birthweight it has limited use in recommending a caesarean section (Margareta et al., 2005). The presence of maternal diabetes mellitus and its association with macrosomia has also been identified as a risk factor (Margareta et al., 2005, Walsh et al., 2011, Malinowska-Polubiec et al., 2015).

1.5.2 Shoulder dystocia

Shoulder dystocia was considered to be a major risk factor for OBPP (Evans-Jones et al., 2003, Margareta et al., 2005, Foad et al., 2009, Walsh et al., 2011). The rate of shoulder dystocia has been reported as 1.4% of all deliveries and 0.7% of all vaginal births (Hansen and Chauhan, 2014). However, the ability to predict the occurrence of shoulder dystocia has been found to be unreliable (Mehta and Sokol, 2014) and while strongly associated with OBPP it was not always present. A literature review of the incidence of OBPP found that shoulder dystocia was not present in 45% (USA) and 47% (other countries) of vaginal births resulting in OBPP (Chauhan et al., 2014). Likewise, only 55% of cases were associated with shoulder dystocia in an incidence study conducted in Ireland (Walsh et al., 2011). Those cases complicated by shoulder dystocia had significant differences noted in infant birthweight and duration of labour but were no more likely to result in permanent disability than those without shoulder dystocia.

Training in management of shoulder dystocia has seen different outcomes. No significant change in incidence was observed by Walsh et al. (2011) while Crofts et al. (2015) found significant benefits to introducing long term training programmes in its management. While shoulder dystocia's presence or absence does not preclude from sustaining an OBPP, awareness of its possibility and subsequent management was important to minimise complications during delivery.

1.5.3 Modifiable risk factors

The ability to identify and subsequently modify risk factors of any condition is an important method of managing incidence. This ability in OBPP was complicated by the fact that some cases had no predisposing factors. In a large survey in the United Kingdom and Republic of Ireland (776,618 live births) no predisposing factors were found in 9% of cases (Evans-Jones et al., 2003). While associated with a lower risk, birth by caesarean section did not offer complete protection from OBPP (Evans-Jones et al., 2003, Margareta et al., 2005, Walsh et al., 2011, Chauhan et al., 2014). The highest frequency of OBPP among infants delivered by caesarean section was found in the weight class of <3499g (Margareta et al., 2005). This finding lends support to the body of evidence that suggested causes other than downward traction during delivery may contribute to OBPP (Gherman et al., 1999).

A retrospective, case-control study by Zuarez et al., (2014) examined potential modifiable risk factors in OBPP. They identified several independent predictors including maternal age >35years ($p = 0.01$; odds ratio (OR) 2.7; 95% confidence interval (CI) 1.3 to 5.7), estimated fetal weight before delivery ($p < 0.0001$; OR 2.5; 95% CI 1.7 to 3.8, for each 500 g increase), vaginal birth after caesarean ($p = 0.02$; OR 3.3; 95% CI 1.2 to 8.8) and vacuum extraction ($p = 0.02$; OR 3.6; 95% CI 1.2 to 10.3). However, they concluded that very few of these risk factors were modifiable. This suggested that OBPP was an unpredictable, unavoidable event that needs to be managed by best practice guidelines. However, due to the obvious complexity of the problem one cannot follow rigid guidelines but respond to how each case presents on an individual basis.

1.6 Prevalence of OBPP

The historical belief that recovery rates of OBPP were very positive meant that, despite a high incidence rate, the actual prevalence of permanent impairment was lower. Several studies have examined recovery rates of OBPP. However, their quality was low, most retrospective in design presenting data from specialist centres, thus introducing a selection bias. A systematic review by Pondaag et al. (2004) identified 42 studies examining natural history in OBPP, none of which met the 4 inclusion criteria which were (1) prospective design, (2) population established on demographic basis, (3) follow up at least 3 years and (4) assessment at end stage recovery was accurate and reproducible. Of the 42 studies 35 met one criterion and 7 met two criteria. As no study presented a prospective, population based, cohort study with sufficient follow-up and proper scoring system it was concluded that there was insufficient scientific evidence of the commonly held belief of an excellent prognosis for this condition. Consequently, caution was advised in predicting excellent recovery too soon and active treatment should be sought to minimise life-long limiting implications.

More recently Foad et al. (2009) examined recovery rates in 11 studies and found a spontaneous recovery rate of 64%. The quality of the studies was similar to Pondaag et al. (2004) with only one being prospective in design. This lack of population based studies contributed to the lower spontaneous recovery rate. The most robust study was a prospective cohort study based on a demographic population over a two year period (Lagerkvist et al., 2010). It found that by 18 months the prevalence of OBPP was 0.46 per 1000 live births compared with an incidence rate of 2.9 per 1000 live births. This meant that 82% of children with OBPP at birth had fully recovered. While it was positive that over 80% of cases of OBPP spontaneously recover, a persisting 20% required careful management to ensure achievement of maximum potential.

1.7 Type of injury

OBPP is a peripheral nerve injury. It can be easily diagnosed at birth as the affected arm presents as a flail arm. Use of appropriate investigations and clinical assessment over time determines the extent of the injury and the affected nerves. The severity of the lesion can be defined in terms of peripheral nerve injury as originally described by Seddon and Sunderland (1978) (Table 1.4).

Differentiating between pre and post-ganglionic lesions in OBPP facilitates optimal treatment planning (Menashe et al., 2015). A pre-ganglionic lesion is an avulsion of the nerve root. These cannot recover spontaneously, only nerve transfer can restore denervated muscles. Presence of Horner’s sign indicates that the lesion is preganglionic. A postganglionic lesion is distal to the sensory ganglion. Both a proximal stump and distal nerves beyond the zone of nerve injury are present and permit reconstruction with nerve grafts. A neuroma forms when torn nerves attempt to re-grow and heal themselves. Scar tissue develops around the injury and can hinder recovery. This may need to be excised to facilitate active recovery.

Table 1.4: Peripheral nerve classification

Classification	Description
First Degree (Class I) Neurapraxia	Temporary interruption of conduction without loss of axonal continuity – spontaneous recovery
Second Degree (Class II) Axonotmesis	Loss of relative continuity of axon and its covering of myelin with preservation of connective tissue framework – spontaneous recovery possible but takes time
Third Degree (Class III) Axonotmesis	Lesion of endoneurium but epineurium and perineurium remain intact – surgical repair may not be required
Fourth Degree (Class IV) Axonotmesis	Only epineurium remains intact – surgical repair required
Fifth Degree (Class V) Neurotemesis	Complete transection of nerve – recovery not possible without surgery
Avulsion	Nerve root is completely detached from spinal cord – preganglionic lesion

1.7.1 Clinical classification

The most widely used classification system for OBPP is the Narakas' Classification. This classification has four groups based on a clinical continuum of roots affected. The original classification system was further modified by Al-Qattan et al. (2009) and is presented in Table 1.5. This modification subdivided group II based on active wrist extension recovery. In a retrospective study of 581 cases with strict criteria applied, a clinical hypothesis that children with C5-7 nerve injuries and active wrist extension against gravity before 2 months of age had a better chance of spontaneous recovery was tested and found to be true.

Table 1.5: Modified Narakas' Classification of obstetric brachial plexus palsy

Brachial Plexus	Nerves	Findings	Narakas' Group
Upper	C5, 6	Weakness of shoulder external rotation, abduction & elbow flexion/supination. "Waiter's Tip" position	I – Erb's Palsy
Middle	C5, 6, 7	As above plus elbow flexion/supination paralysis & loss of wrist extension	II – Extended Erb's Palsy
		Subdivision	
		Active wrist extension before 2mths	IIa
		No active wrist extension before 2mths	IIb
Lower	C8, T1	Good shoulder and elbow movement Floppy hand with claw-like deformity	Klumpke's Palsy (rare)
Complete	C5-T1	Flail arm	III
	C5-T1	Flail arm plus Horner's sign	IV

Adapted from Al-Qattan et al. (2009)

The upper plexus represented by group I and II, was the most commonly occurring injury, with reports of an incidence of between 70-91% in the literature (Evans-Jones et al., 2003, Kozin, 2008, Lagerkvist et al., 2010). Despite being the most prevalent they were found to have the best prognosis for recovery with 95% of group I and 78% of group II showing complete recovery at 18 months (Lagerkvist et al., 2010).

Group III describes complete plexus palsy (C5-T1) with total paralysis of the hand and arm. Group IV describes a complete plexus palsy associated with Horner's syndrome, a consequence of damage to the sympathetic trunk. Sixteen percent of cases were attributed to these two groups in Lagerkvist et al. (2010) while Evans-Jones et al. (2003) reported 6.5% complete plexus lesions. These have the poorest outcome with 61% having persistent impairment at 18 months (Lagerkvist et al., 2010). The odds of complete recovery at 6 months were found to be 11 times higher for group I/II than for group III/IV (Foad et al., 2009). They require early nerve surgery to improve hand function.

Klumpke's palsy (C8-T1) involves the lower trunks and is rarely seen, with a 1% incidence reported in the literature (Lagerkvist et al., 2010).

A classification system allows improved communication with peers regarding both presentation and possible clinical management pathway. Narakas' classification, while not functional in its description, continues to be used widely, both clinically and in research.

1.8 Initial assessment

Management of OBPP begins in infancy and continues into adulthood. Careful assessment at the initial stages is crucial to direct appropriate management to ensure maximum neurological recovery. As previously discussed in Section 1.6 the majority of infants recover fully. For the remaining infants microsurgical intervention was recommended based on expected deficits predicted mainly by clinical findings (Lagerkvist et al., 2010, Malessy et al., 2011, Bade et al., 2014). Through combined use of clinical assessment tools, imaging studies and neurophysiological investigations the need for microsurgery was defined. The following section evaluates the contribution of each of these measures to this decision process.

1.8.1 Clinical assessment tools

Clinical assessment of active muscle return has been identified as the most reliable method of predicting outcome (Lagerkvist et al., 2010). Currently, microsurgical decisions are predominantly guided by the findings of two scales of active muscle return: the Toronto Test Score (TTS) and the Active Movement

Scale (AMS). The TTS is used to guide the surgical decision process by three months of age while the AMS can be used up to 15 years of age.

1.8.1.1 Toronto test score

This scale quantifies upper limb function and aids in predicting recovery in children with OBPP. Five upper limb movements are assessed; “elbow flexion and extension”, “wrist extension”, “digital extension” and “thumb extension”. Each of the listed motor functions is allocated a numeric value from 0-2 based on active movement observed (Figure 1.2). A maximum score of 10 is possible. A combined score of <3.5 at 3 months or older has been found to be a reliable indicator for microsurgery (Michelow et al., 1994).

Gravity Eliminated	**Score**
No Contraction	0
Contraction, no motion	0.3
Motion, <50%	0.3
Motion, >50%	0.6
Full motion	0.6
Antigravity	
Motion, <50%	0.6
Motion, >50%	1.3
Full motion	2

Adapted from Michelow et al. (1994)

Figure 1.2: Toronto Test Score

1.8.1.2 Active movement scale

This AMS, described by Curtis et al. (2002) provides information on the range of motion (ROM) and strength of different movements of the upper limb within available ROM. Assessing all 15 movements provides information on the entire plexus. Each of the following upper extremity motor functions is tested and assigned a score of 0-7: “shoulder flexion”; “shoulder abduction”; “shoulder adduction; “shoulder internal rotation”; “shoulder external rotation”; “elbow flexion”; “elbow extension”; “forearm pronation”; “forearm supination”; “wrist flexion”; “wrist extension”; “finger flexion”; “finger extension”; “thumb flexion”; “thumb extension” (Figure 1.3).

Gravity Eliminated	Score
No Contraction	0
Contraction, no motion	1
Motion, <50%	2
Motion, >50%	3
Full motion	4
Antigravity	
Motion, <50%	5
Motion, >50%	6
Full motion	7

Adapted from Curtis et al. (2002)

Figure 1.3: Active Movement Scale

1.8.2 Validity and responsiveness

No studies have evaluated the validity or responsiveness of the TTS. No study has examined responsiveness of the AMS. However; one has examined the validity of the AMS in quantifying shoulder and elbow movement in children with OBPP (Bialocerkowski and Galea, 2006). It found that experienced paediatric physiotherapists overestimated range of active shoulder and elbow movement by one grade in children aged 6 months to 6 years compared with two-dimensional motion analysis. However, methodological limitations of a lack of variation in examination order, details of assessor competence and insufficient detail for accurate repetition of the study limited interpretation of findings.

1.8.3 Reliability

Both inter/intra-observer reliability of the TTS, AMS and modified Mallet scale were evaluated by a study by Bae et al. (2003). Two trained orthopaedic surgeons examined 80 consecutive children, representing the full spectrum of OBPP, during two separate sessions in a randomised order. Examinations were performed within one week of each other. A power analysis indicated that a total sample of 35 would provide 80% statistical power (b=0.2) to detect “good” intra and inter-observer reliability. A larger sample was collected due to the hypothesis that there may be age related differences in reliability of the measures studied. Their results are presented in Table 1.6.

Table 1.6: Reliability of outcome measures

k: Mean Kappa Coefficient (range); r: Pearson correlation coefficient (range)

Adapted from Bae et al. (2003)

	Intra-observer individual components	Intra-observer aggregate score	Inter-observer individual components	Inter-observer aggregate score
Modified Mallet Scale	k = 0.76 (0.64-1.00)	r = 0.92 (0.80-0.97)	k = 0.78 (0.25-0.87)	r =0.78
Toronto Test Score	k = 0.73 (0.50-1.00)	r = 0.92 (0.81-0.98)	k = 0.51 (0.21-0.80)	r =0.82
Active Movement Scale	k = 0.85 (0.54-1.00)		k = 0.66 (0.22-1.00)	

The TTS demonstrated excellent intra-observer reliability with inter-observer reliability for individual components slightly lower but still corresponding to a good level of agreement. Assessment of thumb extension in the 6 month to 2 year age group was the most reliable between examiners (kappa 0.80) while elbow extension between 1 to 6 months of age was least reliable (kappa 0.21). Total test score was found to have a highly significant positive Pearson correlation for intra-observer reliability. This provided strong support for the use of the TTS in guiding decisions for microsurgery.

The AMS had high intra-observer reliability of individual elements although age impacted on the measures repeatability. The lowest intra-observer reliability was for forearm supination at 2-5 years of age and shoulder internal rotation at 1 to 6 months of age (kappa = 0.54 for both). They also found lower agreement between examiners, with the lowest inter-observer reliability for individual components being elbow extension in the 1 to 6 month group at kappa = 0.22.

In conclusion, the evidence for the psychometric properties of widely used outcome measures for OBPP is sparse. Reliability studies predominate and have demonstrated age dependence, with reliability increasing with age.

Further study to establish the psychometric properties of the most robust clinical measures has been recommended (Bialocerkowski et al., 2013).

1.8.4 Instrumented assessment

While clinical assessment has been found to be the most accurate at predicting outcome; instrumented assessment can augment prediction accuracy. The different instrumented options are: imaging studies such as computerised tomography or magnetic resonance myelography, magnetic resonance imaging (MRI) and neurophysiologic investigations of nerve conduction studies and electromyography (EMG). Instrumented assessments can identify the nature and exact location of the lesion thereby directing an optimal management approach. The benefits of each are briefly discussed below.

1.8.4.1 Imaging investigations

The differentiation between pre and post ganglionic lesions was described in Section 1.6. Pseudomeningoceles (PM) are indicative of lesion severity as they suggest a nerve root avulsion where the arachnoid and dura, that invest the nerve root, are torn and cerebrospinal fluid leaks in the perineural soft tissue (Hawk and Kim, 2000). These can form due to the forceful distraction of the plexus during birth. Computerised tomography myelography, the most reliable instrument in detecting avulsion injuries, was identified as the preferred initial imaging modality (Yoshikawa et al., 2006, Menashe et al., 2015). Additional studies of standard magnetic resonance myelography and contrast material-enhanced MRI were recommended to enhance the understanding of the actual injury (Yoshikawa et al., 2006). Both methods accurately identified PM best in the coronal plane with corroboration on sagittal images (Menashe et al., 2015). PM can also be identified by MRI in children with upper and lower lesions even in the first few days of birth (Yilmaz et al., 1999). As a consequence, it was concluded that MRI findings can be predictive of prognosis. However, it has been reported that posttraumatic neuromas, a highly sensitive and specific MRI finding for postganglionic injury, have proved difficult to visualise (Menashe et al., 2015). Therefore, while MRI was useful in determining side of injury, predicting level of involvement was difficult.

1.8.4.2 Neurophysiologic investigations

Neurophysiologic investigations consist of sensory/motor nerve conduction and needle EMG studies. They provide information on the level of lesion and potential for spontaneous recovery but their accuracy has been questioned with potential to over predict recovery (Clarke and Curtis, 1995). Motor nerve conduction studies provided good early prognostic indexes for neurological outcome in infants with OBPP despite acknowledged limitations, namely co-stimulation of neighbouring nerves (Yilmaz et al., 1999, Heise et al., 2004). The most effective nerves at predicting recovery were the axillary nerve for C5-6 level; proximal radial nerve (triceps) for C5-6 and C7; ulnar nerve for C8-T1 but not C7 (Heise et al., 2004). Motor nerve conduction studies were not recommended as a substitute for careful clinical examination but an adjunct providing more information as to the need for surgery at 3 months of age.

The literature suggests that EMG is not a useful investigative tool to predict recovery in children with OBPP or guide surgical decisions. This was mainly due to two reasons. Firstly, limitations in its application in infants impacted on the accuracy of results. These included lack of cooperation required for assessment of voluntary activity, collateral sprouting and aberrant re-innervation which can account for spontaneous activity detected by EMG that is neither lasting nor functional (Heise et al., 2007). Secondly, the use of EMG alone has been found to result in over optimistic predictions of clinical recovery which limits its clinical usefulness (Yilmaz et al., 1999, Heise et al., 2007). Furthermore, EMG does not correlate well with clinical assessment of movements identified as important prognostic parameters for OBPP, namely shoulder abduction, elbow flexion and extension. EMG scores were significantly higher than clinical scores resulting in overestimation of clinical recovery (Heise et al., 2007).

In conclusion, imaging techniques and neurophysiological investigations do have a role in improving the accuracy of prediction of outcome. They can help identify pre and post ganglionic lesions thereby informing optimal management strategies. However, root avulsion and poor prognosis cannot be excluded by these studies alone. The general consensus of the literature was that clinical assessment is the best method for predicting outcome with judicious use of investigative studies described.

1.9 Microsurgical nerve surgery

Children presenting with OBPP are complex with a range of severity and prognosis. The patterns of re-innervation and recovery are neither fully understood nor predictable. Methodologically sound articles on natural history of OBPP are scarce mainly due to current best practice supporting early surgical intervention in carefully selected patient groups to maximise functional outcome in children (Grossman, 2000, Birch et al., 2005, O'Brien et al., 2006, Vekris et al., 2008, Abzug and Kozin, 2010, Malessy et al., 2011, Mencl et al., 2015). While the necessity of surgical intervention has been acknowledged in certain patient groups, there was no definite consensus underpinning exact indications for, and timing of surgical intervention in the literature. This section discusses current literature on microsurgery.

1.9.1 Indications for, and timing of, microsurgery

1.9.1.1 Spontaneous recovery and complete lesions

As discussed in Section 1.8 instrumented assessments can aid assessment but clinical evaluation of active muscle recovery over time best informed prognosis. A clearer decision process for both the milder and more severely affected children exists. For children with early and full spontaneous recovery there was no indication for surgical or conservative management.

Children with severe injury, defined as neurotemesis or avulsion of spinal nerves, were identified by one month old using a validated assessment model (Malessy et al., 2011). This three item assessment performed at one month old (strength of elbow flexors and extensors; present or absent motor unit potential of biceps) predicted outcome correctly in 93.6% of infants. Clinical testing alone was 80.8% accurate while addition of EMG increased correct predictions by 13%. Malessy et al., (2011) validated the assessment model using two separate cohorts in different countries. Sixty infants with OBPP were included in the first group and 13 in the second. The three item assessment was administered and demonstrated a high accuracy of prediction with the test correctly predicting outcome in 88.3% for one cohort and 84% in the second cohort. From these results it was recommended that severely affected patients should be referred to a specialist centre to facilitate clear management strategies for caregivers, ensure appropriate management and correct timing of surgery. Further support for early intervention was highlighted by Gosk et al. (2014) when a significant difference between the degree of hand width/length and level of useful or useless function in children with complete lesions was identified. There was no correlation between the degree of decreased dimensions and age, suggesting that the disparity between limbs occurred in very early childhood and did not increase with age. This further supports early intervention in complete plexus lesions to minimise muscle atrophy and long term functional consequences.

The general consensus in the literature is that microsurgical intervention for complete lesions should occur within the first 2-3 months of life to maximise reanimation of the hand (Birch et al., 2005, O'Brien et al., 2006, Bade et al., 2014, Mencl et al., 2015). While this was often to the detriment of early recovery of the shoulder and elbow, this temporary side effect was outweighed by the fact that without a functional hand the arm has reduced functional capacity (Mencl et al., 2015).

1.9.1.2 Upper trunk lesions

For children who demonstrate partial recovery the indications for, and timing of surgical intervention is controversial. Management protocols from a variety of centres, based both on clinical experience and outcome data, have been presented in the literature. However, no definitive agreement exists as to which approach was superior. The various approaches are briefly outlined below.

1.9.1.2.1 Indications for surgery

It has been identified that median strength of shoulder external rotators, elbow flexion and forearm supination at 3 months were significantly different between those who recovered fully and those with permanent disability (Lagerkvist et al., 2010). Elbow flexion was the strongest predictor, supporting its historic use for indicating surgical intervention (Malessy et al., 2011). Despite the positive predictive ability of active biceps return, current practice recommends evaluation of more than one muscle group to indicate surgical need in an effort to avoid unnecessary surgery. A Canadian group have published their criteria for surgical intervention in the patient group with partial recovery (Clarke and Curtis, 1995). The first criterion was a TTS of ≤3.5 at 3 months. Should the child pass this test then the surgical decision was deferred. At 6 months of age indications were less defined and cases selected for surgical intervention were based on surgeons' experience. At nine months of age a "Cookie Test" was performed. This stated "the child must bring a cookie to their mouth with pure active elbow flexion". If they failed, operative management was recommended. This algorithm was similar to that used at Texas Children's Hospital outlined by Shenaq et al. (2004).

In addition to the above algorithm, the influence of active wrist extension has been highlighted. As outlined in Section 1.6.1 the amended Narakas' Classification recognised the different outcomes for those with or without active wrist extension (Al-Qattan et al., 2009). The absence of wrist extension in the presence of either active or absent biceps was highly predictive of patients who benefited from surgical repair by a maximum of 5 or 6 months (Grossman, 2000, Fisher et al., 2007). Furthermore, the presence of satisfactory antigravity biceps function was not predictive of good recovery of gross shoulder function, careful monitoring of children until at least 2 years of age was crucial in ensuring timely intervention based on clinical findings (Grossman, 2000, Fisher et al., 2007, Bade et al., 2014).

Bade et al. (2014) identified a small subset of patients who, despite not meeting the common criteria for surgical intervention, may still benefit from microsurgery. They examined 17 subjects who passed the criteria outlined by the Canadian group but had deficient active shoulder movement i.e. absent external rotation with limited shoulder flexion and abduction. Surgical intervention was offered to this subgroup, 14 accepted and three declined. While the sample size did not reach statistical power, preliminary results demonstrated that all patients in the operated group gained some active external rotation. Five patients required further intervention and two of the three subjects, who declined surgery, had no further spontaneous recovery. The authors advised that no substantive conclusions could be made due to the limitations of the study however their findings were interesting, further highlighting the complexity of nerve recovery.

1.9.1.2.2 Timing of surgery

Concern has been expressed in the literature that surgical decisions for upper plexus lesions based on findings at three months of age resulted in surgical intervention in some patients who would have otherwise recovered spontaneously (Michelow et al., 1994, Clarke and Curtis, 1995, O'Brien et al., 2006, Fisher et al., 2007, Bade et al., 2014). The literature suggests that if spontaneous recovery was not clear and active movement questionable then surgery was most effective if performed before 6 months of age (Grossman, 2000, Waters, 2005, O'Brien et al., 2006, Mencl et al., 2015). However, one literature review contradicted this conclusion (Ali et al., 2014). They formed a decision analytical model to examine previous studies conducted and evaluated optimal timing of surgical repair with respect to quality of life (QOL). Four treatment strategies in children with persistent OBPP were examined: no repair and repair at 3, 6 and 12 months. For this group of patients repair at 12 months had significantly better outcomes with respect to QOL than earlier interventions. No definitive recommendations can be made from this review. A randomised controlled trial is necessary to determine the best course and timing of intervention.

In conclusion, in recognition of the diversity in presentation, the importance of repeated assessment and monitoring of the extent of the lesion, rate and timing of recovery to guide clinical management was emphasised. While active biceps return was highly predictive of a positive outcome, active return of movement to the whole upper limb as measured by the TTS is currently more widely used as an indicator for microsurgery as early as appropriate. Future long term research to examine functional outcomes is recommended to ensure accurate selection of patients for microsurgical management.

1.9.2 Types of microsurgery

Surgical intervention aims to improve function, not restore normality. In upper trunk lesions the main surgical goal is restoration of shoulder function and elbow flexion while for complete lesions it is to restore hand function. Overall, primary nerve reconstruction was more successful in upper trunk lesions compared with complete lesions (Shenaq et al., 2004, Birch et al., 2005, Terzis and Kokkalis, 2010). Microsurgical procedures for OBPP include direct repair, neurolysis, nerve graft or neurotisation (nerve transfer). This section provides a brief description of microsurgery and its role in management of OBPP.

1.9.2.1 Direct repair and neurolysis

Direct repair is rarely used as the gap to be bridged results in excess tension on the nerve. Neurolysis alone, which involves resection of scar tissue from around and within the nerve, is no longer indicated in OBPP. It has been shown to have inferior outcomes compared with resection and nerve grafting (Clarke et al., 1996, Capek et al., 1998, Lin et al., 2009).

1.9.2.2 Nerve graft

Neuroma resection and nerve grafting is the gold standard for treatment of rupture injuries (Waters and Bae, 2005). A neuroma-in-continuity, often seen in OBPP, is due to failure of the regenerating nerve growth cone to reach peripheral targets. The criteria supporting resection, or not, of a neuroma-in-continuity varied. Intraoperative nerve action potentials have been used as a prognostic aid. If the nerve action potential dropped more than 50% then neuroma resection and grafting was performed (Shenaq et al., 2004). Other investigations used to guide surgical techniques were: intraoperative inspection of the muscle response to electrical stimulation on the nerve root proximal to the neuroma; pre-operative muscle strength; EMG results and MRI findings (O'Brien et al., 2006). Nerve grafting is an anatomical reconstruction of the nerve from a viable proximal nerve to one or more distal targets, using a nerve graft. The distal recipient can be at the level of the trunk, division, cord or terminal nerve. The sural nerve is the most commonly harvested nerve for grafting as its removal has minimal impact on sensation in the lower leg.

Surgical techniques depend on the findings during surgery with a combination of nerve graft and transfer commonly used.

1.9.2.3 Neurotisation (nerve transfer)

The aim of a nerve transfer is to improve axonal flow to a muscle to enhance function. It is used when a nerve graft would be ineffective. Two important considerations when choosing a donor nerve are: it must be expendable, meaning that its selection will not have a negative impact on its original function, it should provide synergistic function with the intended action as this facilitates relearning post re-innervation (Kozin, 2008).

Improvements in microsurgical techniques have provided greater options for nerve transfers in OBPP. Mostly, they were the only option for re-innervation in complete palsies where avulsion injuries were more prevalent (Waters, 2005, Kozin, 2008). Their use in upper and middle trunk lesions was more controversial. While indicated in the following scenarios, the final decision varies with individual surgeons. 1) Late presentation of a child i.e. over one year of age, this is because the transfer will reach the muscle before a graft thereby minimising denervation time; 2) conservatively managed children who do not have a good spontaneous recovery; 3) in the presence of good shoulder function but no biceps activity, then an isolated nerve transfer for elbow function can be performed preserving shoulder function; 4) if intraoperative assessment reveals poor root quality or avulsions; 5) at a later stage if initial surgery did not yield a good functional outcome (Kawabata et al., 2001, Kozin, 2008). The next section briefly evaluates current literature on microsurgery outcomes.

1.9.2.4 Evaluation of outcomes in microsurgical intervention

The objective of microsurgery is to improve upper limb function through facilitation of nerve regeneration. The majority of surgical interventions are a combination of techniques. This is reflected in the literature with no studies directly comparing outcomes of one surgical option over another. To ensure the child can use their affected hand to assist in bimanual activity, restoration of hand function is the initial goal of surgery in complete lesions (Krumlinde-sundholm and Eliasson, 2003). Improved shoulder and elbow function is the primary goal in upper trunk lesions and a second goal in complete lesions.

Substantial improvements in muscle strength have been reported with combinations of neurolysis, nerve grafting and neurotisation in children with less than antigravity strength in biceps, triceps and deltoid at 6 months (O'Brien et al., 2006). Donor nerves often used to enhance shoulder function are the spinal accessory to suprascapular (Birch et al., 2005) and radial nerve to axillary (Kozin, 2008). Microsurgery has had reported success in useful reanimation of the hand in complete lesions when performed within the first few months of life (Pondaag and Malessy, 2006, Mencl et al., 2015).

Active elbow flexion is crucial for effective functional ability and lack of biceps return presents a challenge to surgeons in the management of OBPP. The transfer of some fascicles of the intact ulnar nerve to the nerve of the biceps was first described by Oberlin in adults (Oberlin et al., 1994). Its use in children with OBPP has been explored in the literature. While the groups have been heterogeneous and small in number they have demonstrated that Oberlin's procedure was a valid option for elbow flexion recovery in OBPP with good functional outcomes (Al-Qattan, 2002, Noaman et al., 2004). Further larger studies are recommended to strengthen the support for the procedure. Lack of elbow extension can also present a functional problem for children with OBPP. A retrospective study examining restoration of elbow extension using nerve graft or transfer found that lesion type, timing of surgery and surgical technique influenced outcome (Terzis and Kokkalis, 2010). In early cases, <6 months old, intraplexus reconstruction of posterior cord using nerve grafts demonstrated good to excellent results. Extraplexus motor donors in late presentation >7 months or multiple avulsions had more variable results. The average denervation time between birth and surgery for all patients was 18 months (range, 2 months-9 years). The long denervation time in the older group confounded results and any interpretations should acknowledge this limitation. However, it did highlight the importance of early surgery in appropriate patients to minimise denervation time due to its impact on the success of nerve surgery.

In conclusion, the role of microsurgery in enhancing nerve regeneration and functional ability in children with OBPP is well recognised. The importance of patient selection, timing of and type of surgical procedure performed is emphasised with further work necessary to determine the most effective procedures and patient groups.

1.10 Secondary Musculoskeletal Consequences

Secondary musculoskeletal contractures and deformities can occur due to incomplete nerve recovery in OBPP. These are a consequence of muscle imbalance resulting in altered forces across joints. The most common of which is between shoulder internal/external rotators and flexors/extensors (Brochard et al., 2014). Musculoskeletal problems include scapular dyskinesis; contractures at shoulder, elbow and forearm; deficits in passive and active shoulder abduction external rotation, elbow flexion/extension (F/E) and progressive glenohumeral (GH) joint deformity (Waters et al., 1998, Pearl and Edgerton, 1998, Nath et al., 2007, Pearl, 2009, Hale et al., 2010, Julka and Vander Have, 2011, Cheng et al., 2015). The musculoskeletal problems impact on bony development and functional performance (Partridge and Edwards, 2004, Newman et al., 2006, Kozin et al., 2010, Sibinski et al., 2012). Appropriate management of these consequences is crucial to minimise negative impact on participation.

1.10.1 Secondary surgeries

The aims of treatment of shoulder sequelae in OBPP are to promote normal bone development and improve functional ability particularly for activities that require external rotation. A meta-analysis of function after secondary soft tissue shoulder surgery concluded it had a positive impact on shoulder function in OBPP (Louden et al., 2013). Many different approaches to address these musculoskeletal problems are described in the literature. These included subscapularis release (Newman et al., 2006, Hultgren et al., 2014, Naoum et al., 2015), combined subscapularis/pectoralis major release with latissimus dorsi and teres major transfer (Ozkan et al., 2004, Pearl et al., 2006, Ozturk et al., 2010, Sibinski et al., 2012, Chomiak et al., 2014, van der Holst et al., 2015) de-rotational osteotomy (Waters and Bae, 2006, Abzug et al., 2010) and triangle tilt surgery to address scapular deformity (Nath et al., 2007, Nath et al., 2014). Selecting the most appropriate procedure to ensure maximum functional outcome is crucial. It depends on radiographic presentation, age and clinical assessment of soft tissue and joint deformity. Their influence is discussed in the following sections.

1.10.1.1 Radiographic presentation

Progressive GH joint deformity is a known consequence of unresolved OBPP. It negatively impacts on the ability to perform adequate functional movement. Prior to any surgical intervention radiographic assessment of GH joint congruency is crucial in selecting the most appropriate procedure (Pearl et al., 2003, Julka and Vander Have, 2011).

1.10.1.2 Age

Similar to primary microsurgery, variable recommendations exist in the literature as to the timing of secondary surgical intervention. According to some authors performing surgery after 3 years and prior to the development of severe contracture increases the likelihood of cooperation with rehabilitation (Chomiak et al., 2014). However, as the ability to impact on remodelling of the GH joint decreases with increasing age this approach has caused concern (El-Gammal et al., 2006, Poyhia et al., 2011). To minimise development of GH joint deformity it has been suggested that secondary surgery should be performed within the first three years of life (Pearl et al., 2006, El-Gammal et al., 2006, Palti et al., 2011). Conflicting reports exist in the literature. A meta-analysis examining function after soft-tissue shoulder reconstruction in OBPP found that increasing age at surgery correlated with decreased likelihood of success (Louden et al., 2013). In contrast, (Nath et al., 2010a) found that triangle tilt surgery allowed remodelling of GH joint, independent of age. Furthermore, while acknowledging the importance of age it was found that outcome was more related to type of paralysis and pre-operative shoulder function than age (Chomiak et al., 2014).

In conclusion no definitive guidelines regarding age of secondary surgical intervention exist. However the age at which surgery is performed has a direct impact on the type of outcome measures that can be used to evaluate outcome. Use of 3D-ULMA is limited in babies and very young children due to cooperation level required and limb size. It has more potential to contribute to the assessment and evaluation process of appropriate surgical intervention in children over 4 years.

1.10.1.3 Microsurgeryôs influence on sec

It has been suggested that microsurgery improves potential function by facilitating greater improvement in muscle strength of the shoulder abductors, and external rotators, thereby increasing the possibilities for secondary tendon transfers (Vekris et al., 2008). However, Aydin et al. (2011) reported comparable results in complete lesions in late reconstruction surgeries with those who had nerve surgery. Subjects with Erb's Palsy had further improvement in external rotation with such surgeries as latissimus dorsi transfers. The study was limited in that it was retrospective and secondary surgeries were completed on failed early nerve surgery candidates. While it presented interesting findings it is not sufficient evidence to discard early microsurgery in favour of late secondary surgeries or vice versa.

1.10.1.4 Clinical presentation

As with all interventions to enhance function, identification of the main problem ensured it was appropriately addressed by the chosen surgery. Improving the capability of current outcome measures will facilitate this process. Determining whether functional impairment was a consequence of contracture, muscle paralysis/weakness, co-contraction or bony deformity was crucial when deciding on the most appropriate surgical intervention (Gu et al., 2000). As with much of the management of OBPP a definitive consensus is lacking in the literature as to the best method of surgical intervention. The following sections briefly outline current surgical approaches described.

1.10.1.4.1 Internal rotation deformity

Hale et al. (2010) found that lack of external rotation was evident at all levels of the Narakas Classification (NC). Weakness of external rotation in the absence of contracture is often treated with tendon transfer alone, if adequate internal rotation is present (Louden et al., 2013, Chomiak et al., 2014, Hultgren et al., 2014). Contrasting results have been found in the comparison of the success rate of surgical techniques to improve shoulder function (Louden et al., 2013). The open technique for soft-tissue shoulder reconstruction surgery had a significantly higher success rate for global abduction compared with the arthroscopic technique. However in the same study, there was no significant difference for the success rate of external rotation as measured by the Mallet scale when comparing the two procedures. Different placement of muscle transfers was a possible reason for this.

While lack of external rotation function has been found to be the main problem in OBPP, the loss of both active and passive shoulder internal rotation has been documented post-surgical interventions to address internal rotation contractures (Pearl et al., 2006, Abzug et al., 2010, Sibinski et al., 2012, Hultgren et al., 2014, Chomiak et al., 2014). This impeded midline function and due consideration for internal rotation should be given when performing any surgery (Abzug et al., 2010, Sibinski et al., 2012). Internal rotation contracture was treated with anterior release and tendon transfers (Pearl, 2009). When an internal rotation contracture was accompanied by GH joint subluxation and dislocation, an anterior release was recommended to reduce the GH joint along with tendon transfers and an internal rotation osteotomy to combat any potential loss in internal rotation ROM (Sibinski et al., 2012).

1.10.1.4.2 Glenohumeral joint deformity

Maintaining or restoring a congruent GH joint in younger patients is crucial for maximum function. Imaging studies have shown that GH joint deformities, as a consequence of muscle imbalance with unopposed internal rotators, were seen as early as the first two years of life in OBPP (Pearl et al., 2003). Increasing loss of passive external rotation was correlated with progressive GH joint deformity, namely increased angles of retroversion and posterior subluxation (Kozin, 2004).

Humeral head subluxation and glenoid deformity prohibit normal shoulder development. Reduction of the GH head realigns the joint and provides opportunity for remodelling over time. While some studies have reported improvement in glenoid development with soft tissue surgery alone (Pearl et al., 2006, Breton et al., 2012) others reported no positive effect with soft tissue release or transfers in isolation (Waters, 2005, Kozin et al., 2010). Other studies have shown that bony surgeries such as relocation (Poyhia et al., 2011) or internal rotation osteotomy (Assuncao et al., 2013) were necessary to improve GH congruency. It has been suggested that GH remodelling capacity decreased after four years (El-Gammal et al., 2006). This was supported by Poyhia et al. (2011) who experienced failed relocation surgeries in the two children >6 years as compared with success in 10 children <5years.

In older patients with long standing internal rotation contractures and significant GH joint deformity, de-rotational osteotomies could place the arm in a more functional position (Waters and Bae, 2006, Abzug et al., 2010). It was acknowledged that this surgery did not improve GH motion but altered the arc of movement to improve function. The amount of humeral rotation required during surgery can be determined by subtracting the degree of active external rotation arc from the amount of external rotation required for functional activities, with conservation of sufficient internal rotation to perform midline activities (Abzug et al., 2010).

1.10.1.4.3 Scapular dyskinesis

Asymmetric and abnormal scapular movement was a frequent concern in OBPP, particularly for parents. It was most often associated with limited GH excursion and an internal rotation contracture. Scapular elevation, or “Putti sign” is recognised by the superior border of the scapula protruding into the trapezius with forced shoulder external rotation in the presence of an internal rotation contracture (Julka and Vander Have, 2011). The majority of secondary surgeries aimed to influence this by directly addressing existing contracture and muscle imbalance.

A scapular deformity termed SHEAR (scapula hypoplasia, elevation and rotation) was described by Nath et al. (2007). They suggested that this deformity was the primary cause, not the result, of the internal rotation contracture and GH deformity. They proposed that the traditional surgical approach of external derotation osteotomy to address internal rotation contracture (Waters and Bae, 2006, Abzug et al., 2010) was insufficient as it did not address the root cause. Consequently, they developed a new surgical approach “Triangle Tilt Surgery” to correct the primary bony deformity seen in SHEAR. This surgical strategy released the distal acromioclavicular triangle from the medial spine of the scapula and medial clavicle by osteotomies of the clavicle and neck of the acromion allowing the distal triangle to tilt back into its neutral position. This relieved the impingement of acromioclavicular triangle on the humeral head and allowed the latter to be positioned passively into a neutral position in the glenoid fossa. It was found to improve function by significantly increasing the aggregate Mallet score (Nath et al., 2007, Nath et al., 2010b) and allow for repositioning and remodelling of the GH joint over a mean follow-up period of 19 months (12-38 months) (Nath et al., 2010a).

However, while positive functional results and GH remodelling have been reported, the theoretical premise that this deformity was the primary cause of deformity conflicted with current understanding of OBPP pathophysiology. As yet no other studies or centres have supported this hypothesis.

In summary, secondary musculoskeletal problems as a consequence of OBPP, in the aftermath of microsurgery or not, present a significant problem for both clinician and the person with OBPP. Several procedures addressing the variety of problems posed have been explored in the literature. There is no definitive consensus as to the most effective or appropriate procedure for each clinical presentation. This is, in part, due to a lack of quality research in the form of randomised controlled trials but also due to heterogeneity in the active recovery of subjects and the ability to objectively assess it. This gap in both the literature and clinical practice needs to be addressed.

1.11 Therapeutic management of OBPP

Conservative therapeutic management of OBPP is essential from birth to maturity with active involvement of parents initially and children when older (Heise et al., 2015). The primary aim of therapeutic intervention is to facilitate muscle function in the affected limb and prevent complications of reduced movement such as contracture or joint deformity (Bialocerkowski et al., 2005). Therapy is delivered by both physiotherapists and occupational therapists and consists of a variety of modalities including: stretching and movement based therapy (Gharbaoui et al., 2015, Brown et al., 2015); botulinum toxin (DeMatteo et al., 2006, Gobets et al., 2010, Michaud et al., 2014); modified constraint therapy (Santamato et al., 2011); splinting (Gharbaoui et al., 2015); neuromuscular electrotherapy (Berggren and Baker, 2015). While these therapies are used regularly in clinical practice the scientific support for their effectiveness is limited with very few studies evaluating their contribution and effectiveness. Michaud et al. (2014) found that botulinum toxin was a useful adjunct to therapy in managing muscle imbalance, co-contraction and contractures in children with OBPP but agreed with Gobets et al. (2010) that a randomised controlled trial was necessary to evaluate its true effectiveness. In a single case study of a home based movement programme, Brown et al. (2015) identified its potential to improve ROM, arm function and movement quality. However, this was in a motivated 17year old girl who had a specific functional goal to which she aspired. This highlights the importance of motivation and active involvement of the child in all therapeutic programmes and the role active exercise has in enhancing function.

1.12 Long term impact of OBPP and client perceptions

Children with OBPP, as with any condition that results in movement dysfunction, are at risk of experiencing adverse effects from compensatory strategies in later life. However, rather than simply measuring objective physical findings, ascertaining patient expectations and opinion on the impact of movement dysfunction on QOL and participation is crucial. This is fundamental in evaluating health outcomes and directing appropriate management.

Studies have indicated that daily functioning in adults with OBPP was worse than peers. A study of adults with OBPP by Partridge and Edwards (2004) reported ADL limitations and concerns with regard to the cosmetic appearance of their arm. This was confirmed by de Heer et al. (2014) who found that young adults with OBPP were significantly worse in general performance ($p < 0.001$) and music/sport performance ($p = 0.008$) than peers as measured by the Disability of the Arm, Shoulder and Hand questionnaire (DASH). The DASH work module was not significantly different but this was possibly due to selection of work that did not necessitate good hand function.

Pain was a prevalent problem with a reported incidence of 54% to 92% in adults with OBPP in the literature (Partridge and Edwards, 2004, de Heer et al., 2014, Ho et al., 2015) and it was worsening in 82% (Partridge and Edwards, 2004). The highest correlation for decreased function in ADL was with pain scales, both for DASH and SF36, suggesting that pain rather than limited arm/hand physical function was the main contributing factor to reduced functional ability (de Heer et al., 2014). The importance of evaluating both musculoskeletal and neuropathic pain symptoms was highlighted by Ho et al. (2015). Children reported pain in both aetiologies but often did not label neuropathic symptoms as pain as they have become integrated into daily life. It was still important to be able to identify them and minimise their impact on children's' lives.

Adolescents with OBPP were found to have a good QOL compared with typically developing peers but functional limitations were responsible for the greatest difference in outcome (Squitieri et al., 2013). Contextual and environmental factors such as family dynamics, finance and therapy appointments were more prominent influencing factors in adults (Squitieri et al., 2013). Despite children with OBPP having lower functional scores than peers, as measured by PODCI and modified Mallet Scale, this did not negatively impact on level of sport participation (Bae et al., 2009). Despite the relatively small numbers (n=85) in this study this was a positive finding that can reassure parents of young affected children.

Increased functional ability and reduced pain were the main categories of expected improvement for adolescents and their parents after any treatment (Squitieri et al., 2013). This was positive as they relate to goals of therapeutic intervention. Further increasing understanding of musculoskeletal contributions to functional limitations and development of pain will enhance management strategies thus addressing the main concerns of the client group.

1.13 Objective measures used in clinical practice

Use of standardised, valid and reliable outcome measures ensures confidence in findings and effective communication between health professionals. The ability to quantify upper limb function is crucial to accurately inform management strategies, measure change over time and effectiveness of interventions.

1.13.1 International Classification of Functioning, Disability and Health

The International Classification of Functioning, Disability and Health, known more commonly as ICF, is a classification of health and health-related domains (WHO 2014). ICF defines three levels of human functioning: body, structure and function; activity; participation. An individual's full and meaningful participation in life is the ultimate aim of any health professional. To facilitate this, accurate assessment of all aspects of the individual's presentation at each level of ICF using appropriate outcome measures with robust psychometric properties is essential (Duff and DeMatteo, 2015).

1.13.2 Outcome measures in OBPP

Therapeutic and surgical interventions aim to enhance activity levels and participation through addressing impairments of body, structure and function. Measures of body, structure and function were the most common clinical measures in OBPP especially in younger children (Chang et al., 2013, Sarac et al., 2015). Reliable measures of body, structure and function are crucial in informing which intervention will be most effective. It has been found that measures of active movement, in particular the modified Mallet scale and TTS, correlated well with measures assessing global and upper limb function such as the Paediatric Outcomes Data Collection Instrument, a QOL questionnaire (Bae et al., 2008).

A systematic review of the psychometric properties of outcome measures used in children with OBPP found that 33 measures assessed ICF domains, however only eight had psychometric evidence of variable quality (Bialocerkowski et al., 2013). Three evaluated the body, structure and function domain of the ICF (Table 1.7). The AMS and TTS were discussed in Section 1.7.1. The modified

Mallet scale, goniometry and three dimensional (3D) motion analysis in assessment of the upper limb are discussed in this section.

Table 1.7: OBPP outcome measures of body, structure and function domain with psychometric evidence

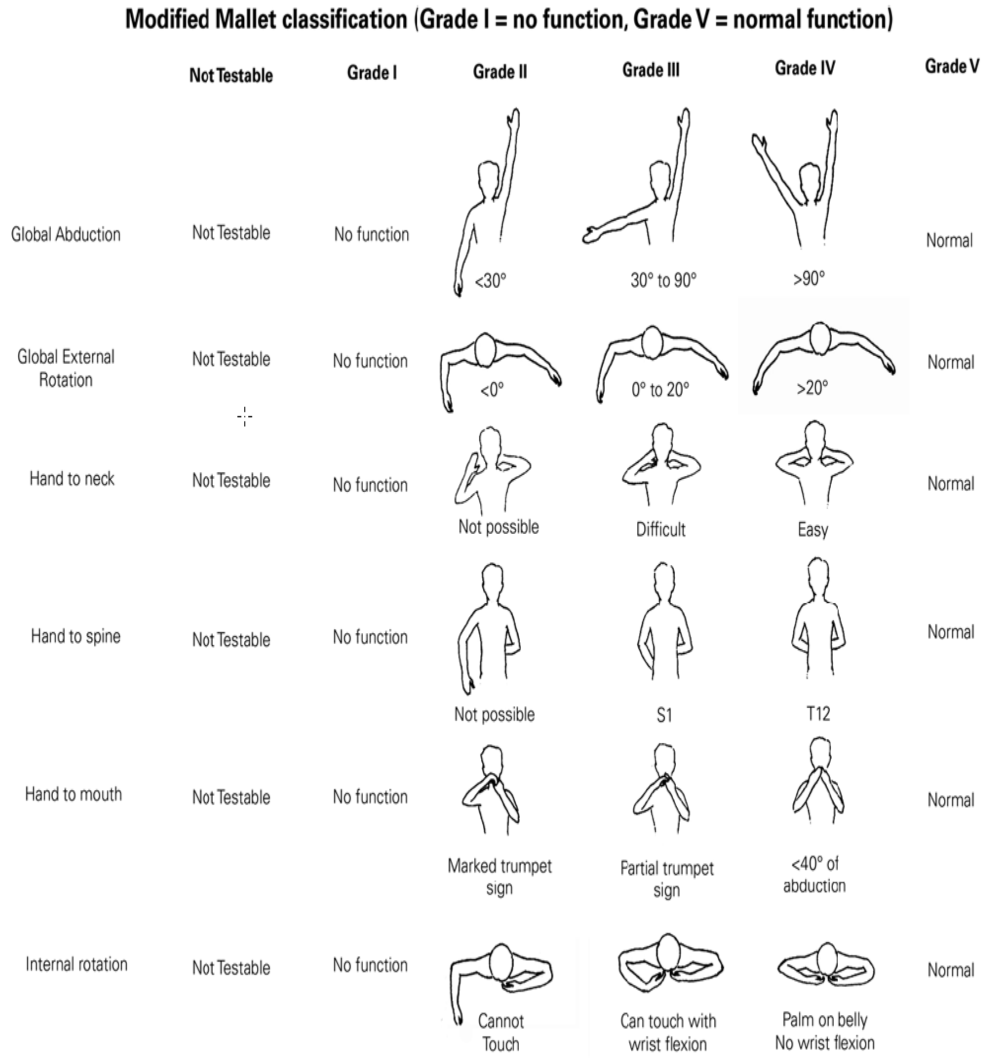
AMS: Active movement scale *Adapted from (Bialocerkowski et al., 2013)*

Outcome Measure	**Description**	**Report on Psychometric Properties**	**Reliability of Individual Components (Kappa)**	**Reliability of Aggregate scores (Pearson Correlation)**	**Validity Results (% Agreement)**
Body, Structure, Function					
Active Movement Scale	Physical examination where combined active movement and muscle strength is quantified based on 15 upper limb movements	Reliability - (Bae et al., 2003, Curtis et al., 2002) Validity - (Bialocerkowski and Galea, 2006)	Bae et al., 2003 Intra-observer: 0.85 (range 0.54-1); Inter-observer: 0.66(0.22-1) Curtis et al., 2002 inter-observer: 0.51 (range 0.33-0.88)	Not reported	Only four movements of AMS were assessed compared with 2D Motion analysis system Elbow Flexion 41%; extension 43%; shoulder abduction 56%; flexion 70%
Mallet Scale	Physical examination as child performs five tasks	Reliability - (Bae et al., 2003)	Intra-observer: 0.76 (range 0.64-1); Inter-observer: 0.78 (range 0.25-0.87)	Intra-observer: 0.92 (range 0.80-0.97); Inter-observer: 0.78	-
Toronto Test Score	Physical examination as child performs five upper limb movements	Reliability - (Bae et al., 2003)	Intra-observer: 0.73 (range 0.5-1); Inter-observer: 0.51 (range 0.21-0.8)	Intra-observer: 0.92 (0.81-0.98); Inter-observer: 0.82	-

1.13.2.1 Modified Mallet scale

The modified Mallet scale (Figure 1.4) has been widely used to classify shoulder function in children with OBPP (Abzug et al., 2010) and to assess impact of secondary surgical intervention (Waters and Bae, 2005, Nath et al., 2010b, Kozin et al., 2010, Chomiak et al., 2014).

The child actively performs six different shoulder movements: Abduction; External and Internal rotation; Hand-to-Neck; Hand-to-Spine and Hand-to-Mouth. Each movement is graded on a scale of 1 (no movement) to 5 (normal motion similar to unaffected side) with a possible maximum score of 30 by visual estimation.



Adapted from Abzug et al. (2010)

Figure 1.4: Modified Mallet scale

While it records the achievement of functional positions of the upper limb, the individual contributions of each joint to the movement are not recorded. In addition, the modified Mallet scale does not measure true degree of change in shoulder function but rather changes between defined grades. This may lead to underestimation of change and an inability to discriminate at which joint, if any, change has occurred.

1.13.2.1.1 Psychometric properties of modified Mallet scale

Neither validity nor responsiveness of the modified Mallet scale has been examined. Its reliability was found to be excellent for intra and inter-observer reliability with a mean kappa of 0.76 (range, 0.64 to 1.00) and 0.78 (range, 0.25 to 0.87) respectively (Bae et al., 2003). Good intra-observer reliability for all individual components was seen with no individual component having a kappa lower than 0.64. However, a larger range was seen in inter-observer reliability with some component movements showing poor examiner agreement. This was lowest in the Hand-to-Spine Task in children 2-5 years of age (kappa 0.25). The aggregate scores of the modified Mallet Scale demonstrated strong intra-observer (0.92, range 0.8-0.97) and inter-observer (0.78 $p<0.001$) reliability in all age groups. This was important as aggregate rather than individual scores were generally used to assess effectiveness of interventions.

1.13.2.2 Assessment of ROM

Active and passive ROM, measured by visual inspection using a goniometer, were commonly used in assessment of OBPP (Chang et al., 2013). Accurate measurement of any motion is dependent on the assessor's ability to be positioned perpendicular to the plane of motion. Due to the structure of the shoulder complex elevation can occur in a variety of planes clinically referred to as forward flexion (sagittal), abduction (coronal) and scapular (scaption). This level of mobility renders accurate visual inspection of 3D movement very difficult in clinical assessment. While the Society of American Shoulder and Elbow surgeons recommend that shoulder elevation be assessed at maximum ROM, they do not indicate which plane of motion to use.

One study by Finley et al., (2015) compared 3D-ULMA of humeral elevation with goniometric measurement. This study found that maximum elevation occurred between true sagittal and coronal planes approaching the scapular plane. In addition, maximum elevation found by 3D analysis was lower than that reported by goniometric assessment (Finley et al., 2015). Position of the examiner with respect to the actual plane of motion of the arm may account for this difference. Additional compensatory movements such as trunk lateral flexion may also have influenced evaluation of maximum elevation using goniometry. This highlighted the limitations of visual inspection of dynamic movement.

Large variability in reliability coefficients have been found for goniometric assessment of passive and active ROM of the shoulder complex in adults with no studies found that reported on reliability in the paediatric population. Intraclass correlation coefficients (ICC) ranged from 0.28 to 0.99 for both intra-observer and inter-observer reliability with intra-observer being predominantly more reliable (Riddle et al., 1987, de Winter et al., 2004, Wilk et al., 2009, Kolber et al., 2012). As the majority of studies only reported reliability coefficients, interpretation of results was limited due to the influence of within-subject variability on ICC results. Two studies using similar measurement instruments reported absolute measures with contrasting results (de Winter et al., 2004, Riddle et al., 1987). de Winter et al. (2004) evaluated inter-observer reliability of passive ROM of abduction and external rotation with a digital inclinometer. They concluded that measurements, while reliable for group comparisons (ICC 0.83 to 0.90), were not reliable for individual comparisons [Mean difference (standard deviation (SD)) – Abduction: 0.9º(9.6º) ICC 0.28 to 0.83; External rotation: -6.6º(9.5º) ICC 0.56 to 0.90]. The second study by Kolber et al. (2012) examined elevation in the scapular plane using both goniometry and a digital inclinometer in 30 asymptomatic adult subjects. They concluded that both methods had acceptable reliability with goniometry inter-observer standard error of measurement (SEM) 2.9º, minimal detectable change (MDC) 8º; ICC 0.92 (0.83 to 0.96) and inclinometer inter-observer reliability SEM 3.4º; MDC 9º; ICC 0.89 (0.77 to 0.95). Different movements were assessed which may have influenced results.

The circumstances surrounding the protocol of assessing ROM using a goniometer was quite different to 3D analysis of active performance of functional tasks. This makes direct comparison of results impossible. While the population group OBPP have not been specifically examined conflicting reports of reliability of goniometric measurement of the upper limb in adults exist in the literature. It was dependent on motion assessed, standardisation of subject position and observers. There was no consensus as to an acceptable error of measurement. de Winter et al. (2004) chose 10º based on clinical experience. This was deemed appropriate for children with OBPP as to change classification grade in the modified Mallet scale a difference of 20º in External Rotation and 30º in Abduction was necessary.

ROM assessment provides information with regard to available passive and active ROM within a joint. While an important component to measure, it alone does not inform how joints work together to provide functional movement. This gap in objective assessment can potentially be filled by 3D motion analysis.

1.13.2.3 3D motion analysis

3D motion analysis is a non-invasive method of accurately measuring how one moves in daily functional activities. This method of quantitative movement analysis has a role in improving understanding of how the body works. It is the reference standard for gait analysis in clinical practice and has contributed significantly to the understanding of both normal and abnormal gait patterns and appropriate interventions that enhance function (Narayanan, 2007, Wren et al., 2011).

Three-dimensional upper limb motion analysis has proved more difficult to implement into clinical practice. This is due to lack of standardisation and consensus in the literature resulting, in part, from the complex nature of upper limb motion (Petuskey et al., 2007). A reliable method of 3D-ULMA could provide an objective measure of the performance of activities of daily living (ADL) thus providing a valuable method of functional evaluation to inform clinical management.

As discussed in the preceding sections the ability of existing outcome measures to assess the contribution of individual joints to functional movement in OBPP is inadequate. In children with OBPP, GH and scapulothoracic (ST) kinematics must be further clarified to advance understanding of aetiology, prevention and treatment of complex shoulder deformity (Eismann et al., 2015). It is proposed that 3D-ULMA could be used in conjunction with current clinical scales and assessment of pain, muscle strength and ROM. This additional information provided by 3D-ULMA while performing functional tasks is hoped to increase understanding of characteristic movement patterns in OBPP, contribution of individual joints and provide an objective outcome measure for pre/post-surgical intervention.

1.13.2.3.1 Current research in 3D-ULMA

Several studies have explored 3D-ULMA's validity, reliability and ability to detect change in different subjects including typically developing adults and children (Magermans et al., 2005, Petuskey et al., 2007, Jaspers et al., 2011c, Roren et al., 2013, Schneiberg et al., 2010); children with OBPP (Mosqueda et al., 2004, Wang et al., 2007, Duff et al., 2007, Fitoussi et al., 2009, Russo et al., 2014, Russo et al., 2015), children with cerebral palsy (Mackey et al., 2005, Reid et al., 2010, Jaspers et al., 2011b, Brochard et al., 2012, Klotz et al., 2014, Vanezis et al., 2015, Schneiberg et al., 2010) and other conditions (Ludewig and Cook, 2000, Rundquist et al., 2003, Hingtgen et al., 2006). This literature has highlighted both the benefits and difficulties of 3D-ULMA. Despite the inherent difficulties, the additional understanding of movement provided by 3D-ULMA was emphasised. However, further evidence is needed to enhance and support its clinical implementation.

Test-retest reliability of 3D-ULMA in TDC has been examined in previous research (Vanezis et al., 2015, Lempereur et al., 2012, Jaspers et al., 2011c, Reid et al., 2010). The exact models used in these studies were not identical as they used different tracking systems, methods of defining joint rotation or estimation of the GH joint rotation centres. However, they all followed ISB recommendations as per Wu et al., (2005). All four studies concluded that 3D-ULMA could reliably quantify upper limb movements in TDC which allows confident comparison of kinematic patterns of TDC with those of specific clinical populations. Further discussion of test-retest reliability of 3D-ULMA in TDC is provided in Chapter 2: Development of Methodology Section 2.4.2.2.4.4.

1.13.2.3.2 The use of 3D-ULMA in OBPP

The following paragraphs explore the literature on the use of 3D-ULMA in OBPP. Their contribution to the understanding of movement patterns and dysfunction in OBPP is briefly described. Finally, the limitations of current literature and reasoning for this research are highlighted.

1.13.2.3.2.1 Evaluating impact of interventions

The ability to objectively evaluate movement quality and the contribution of individual joints to task performance would help direct surgical intervention and assess its effectiveness. The capacity of 3D-ULMA to identify change pre and post-surgery was explored by Fitoussi et al. (2009). Application of the results was limited as they only examined one subject pre and post external rotation osteotomy. However, they found that kinematic evaluation surpassed clinical evaluation using the modified Mallet Scale in identifying change in variables assessed. Clinical evaluation did not reveal a clear limitation in arm abduction or flexion relative to the trunk in the subject with OBPP compared with typically developing controls. Kinematic evaluation, however, demonstrated a clear decrease in amplitude. An arc of 23¯ of motion during elbow F/E and 9.5¯ in abduction/adduction in the subject with OBPP was found, compared with 41¯ and 20¯ in controls respectively. Post-operatively, significant changes were observed within these arcs of movement. The average curve of the subject with OBPP after surgical intervention was similar to the normative curves of the controls. This study suggested that reliable 3D-ULMA provided a more objective measure of surgical outcomes than current outcome measures used, the modified Mallet Scale and AMS. However, further research is required to strengthen these preliminary findings.

1.13.2.3.2.2 Discriminative ability of 3D-ULMA

The ability of an assessment measure to discriminate between typically developing children (TDC) and those with impairment is crucial. The capacity of 3D-ULMA to discriminate between affected and non-affected limbs has been explored in the literature (Mosqueda et al., 2004). Mosqueda et al., (2004) compared 3D-ULMA of 55 children with OBPP with 51 TDC while performing ADL. This study concluded that 3D-ULMA could identify significant differences in motion between affected and non-affected limbs. A limitation was that the model used did not distinguish between the GH and ST joints. They were treated as one joint the “non-existent” thoracohumeral (TH) joint.

A later study by Russo et al. (2014) used a model that distinguished between the GH and ST joints. Twenty children with OBPP were examined performing the modified Mallet Scale. They were compared with 6 unaffected limbs of participants with OBPP. Use of the contralateral unaffected limb in children with OBPP has been found to be comparable to use of an unaffected limb in TDC (Wang et al., 2007). They concurred with earlier studies that 3D-ULMA could discriminate between affected and non-affected limbs. Furthermore, the additional information on individual GH and ST contributions improved its discriminative ability by allowing classification of OBPP subjects according to their severity. This information greatly adds to the understanding of movement patterns in children with OBPP and can inform clinical management. However, while they examined the tasks of the modified Mallet scale, data were collected with the arm statically held at point of task achievement (PTA). It has been concluded that static evaluation of a joint position did not directly correlate with dynamic performance (Fayad et al., 2006). This limited the interpretation of the study's findings in understanding dynamic upper limb task performance which was critical to effective management.

1.13.2.3.2.3 Contributions of individual joints to upper limb function

As discussed earlier existing outcome measures provided general information on function, strength and passive or active ROM of joints (Bae et al., 2003, Wilk et al., 2009, Abzug and Kozin, 2010). They did not assess individual contribution of specific joints to dynamic movement patterns.

Current surgical approaches to manage secondary musculoskeletal deformities propose to improve GH motion by releasing tight structures (Newman et al., 2006, Hultgren et al., 2014), improving active control via tendon transfers (Ozkan et al., 2004, Pearl et al., 2006, Ozturk et al., 2010, Sibinski et al., 2012, Chomiak et al., 2014) or addressing deformity (Waters and Bae, 2006, Nath et al., 2007, Abzug et al., 2010, Nath et al., 2010b). However, no studies have specifically assessed the relative contributions of specific joints to functional activities pre and post-surgical interventions. Therefore, surgery may do nothing more than re-orientate the arc of upper limb movement into a more functional position.

The ability to track dynamic motion provides information as to the coordinated motion of joints thereby improving understanding of their interaction and possible deficits. Inclusion of reliable 3D-ULMA into clinical assessment would greatly enhance the ability to evaluate effectiveness of surgical intervention. As mentioned already, the majority of 3D-ULMA studies of dynamic movement failed to distinguish between GH and ST joints, treating them as the functional but non-existent TH joint. Two studies using 3D-ULMA have explored their contributions to arm elevation (Duff et al., 2007) and performance of functional tasks (Russo et al., 2014, Russo et al., 2015). Two limitations of these studies were the task was not specifically related to a functional activity (Duff et al., 2007) and data were collected statically at PTA (Russo et al., 2014, Russo et al., 2015). While this provided information on joint position at PTA no information was obtained as to the path travelled by the arm to achieve this position.

1.13.2.3.2.4 Potential value of 3D-ULMA as an assessment tool

The main benefits in using 3D-ULMA as identified by this researcher are:

- Its sensitivity in assessment permits evaluation of surgical interventions as highlighted by Fitoussi et al., (2009). 3D-ULMA was found to identify improvements that were not documented by the existing outcome measure predominantly used to evaluate surgical outcomes – modified Mallet scale.
- 3D-ULMA tracks each joint and segment of the upper limb, therefore it can quantify the individual contributions of each joint to functional task performance. The modified Mallet Scale only provides information on global upper limb task performance.
- That it has also been shown to discriminate between children with different levels of severity of OBPP. This enhances the understanding of movement characteristics of affected children and has potential to assist in addressing functional deficits in this population
- Goniometry can only provide information on available active and passive range of motion in specific planes of movement while 3D-ULMA provides objective information as to how this range interacts to perform daily functions.

The existing studies using 3D-ULMA have improved the understanding of movement in children with OBPP but gaps still exist in the literature. In particular, no study has examined the reliability of 3D-ULMA in children with OBPP or the relative contributions of GH and ST joints to dynamic functional task performance been examined. This research study proposed to address these gaps.

1.14 Research question

From clinical experience of managing children with OBPP, the need to improve the quality of outcome measures and understanding of movement patterns was identified by the author. Following a comprehensive literature review of current assessment and management aims of OBPP several gaps became apparent.

Firstly, it was identified that a reliable method of assessing both pattern of movement and contribution of GH/ST joints during functional tasks was necessary to better inform intervention strategies. Secondly, an outcome measure that was more sensitive in evaluating change within individual joints post intervention was lacking. 3D motion analysis is the established reference standard for gait analysis and has been invaluable in enhancing management of gait deviations. Therefore, developing its potential use in assessment of the upper limb should add to our understanding and provide a more objective assessment tool.

Therefore, the aims of this research study were to determine:

¶ Test-retest reliability and intra-observer measurement errors of 3D-ULMA in children with OBPP while performing tasks of the modified Mallet scale.

¶ Its ability to identify discriminative upper limb spatiotemporal and kinematic characteristics between children with OBPP and TDC.

The hypotheses were that:

¶ The chosen model of 3D-ULMA would measure dynamic movement within an acceptable error of measurement.

¶ Children with OBPP would have faster arm movements.

¶ Children with OBPP would use more scapular movement to achieve functional tasks.

¶ Children with OBPP would be biased towards shoulder internal rotation compared with TDC.

No consensus existed in the literature as to a specific model or method of tracking upper limb motion. Therefore, a comprehensive literature review was conducted to determine the most appropriate method of 3D-ULMA for the purpose of this research study. This is detailed in Chapter 2 Development of Methodology.

Chapter 2 Development of Methodology

2.1 Introduction

The literature review identified that despite improvements in medical interventions the incidence of OBPP has not significantly changed (Walsh et al., 2011, Heise et al., 2015). This results in the presence of a consistent cohort of affected individuals at risk of long term functional impairments and in need of therapeutic and surgical management. It was highlighted that despite advances in the use of 3D-ULMA, the exploration of its use in OBPP was limited. In addition, current outcome measures for OBPP did not adequately distinguish between the GH and ST joints during functional task performance. This gap in current literature led to the conception of this research study.

This chapter describes the development of methodology for the purpose of this research study. It will outline the research question posed; joints and segments chosen for analysis; International Society of Biomechanics (ISB) recommendations for joint co-ordinate systems and joint and segment rotation sequences; scapular tracking method; implementation of the chosen upper limb model within the laboratory and final set-up.

2.2 Research question

As the national referral centre for management of children with OBPP the Central Remedial Clinic (CRC) constantly strives to improve service, ensure evidence based practice and provide objective measures of interventions. Evaluation of 3D shoulder kinematics in a clinical capacity has progressed despite the challenges presented by its validity and reliability (Cutti and Chadwick, 2014). A review of related literature in Chapter 1: Introduction and Literature review: Section 1.10.2.3 identified a gap in existing research with regard to reliability of 3D-ULMA and analysis of dynamic scapular motion during functional tasks in children with OBPP. Inherent problems with 3D-ULMA have limited its exploration and use in clinical practice. These include the large ROM available at the shoulder complex with a lack of a cyclical movement task; the complexity of the definition of the GH joint centre, further complicated by the atypical development of the GH joint in children with OBPP; and skin movement artefact in tracking scapular movement (Reid et al., 2010) and humeral axial rotation (AR) (Cutti et al., 2005). Use of 3D-ULMA should acknowledge its limitations but should not preclude exploration and refinement of its development for use in clinical practice. To effectively address the research question the chosen model should comply with existing recommendations for a motion analysis protocol, be able to measure dynamic upper limb function with acceptable reliability. The following sections present the literature review of current available methods and the description of the chosen upper limb model.

2.3 Joint and segments chosen for analysis

There are three segments of the upper limb attached to the thorax by the scapula: the humerus, forearm and hand. Within these are several joints: sternoclavicular; acromioclavicular; ST; GH; elbow, superior and inferior radioulnar, wrist, carpometacarpal and interphalangeal joints. It was beyond the scope, clinical relevance and technical capacity of this study to analyse all joints. Based on the literature review of the main problems for children with OBPP (Russo et al., 2014, Gharbaoui et al., 2015) it was decided to focus on the proximal segment with specific reference to the ST, GH joints and the non-existent, but often referenced, TH joint. The elbow joint was also analysed in specific movements as it was deemed crucial to effective task completion.

2.4 Mechanical model

In choosing the most appropriate mechanical model for the purpose of this research study, a thorough literature search was conducted to identify available models and methods of tracking upper limb movement. In recognition of the importance of scapular movement in children with OBPP, the chosen model needed to accurately track the scapula during dynamic functional movements. The following paragraphs briefly outline the literature review.

2.4.1 Joint and segment definition and joint rotation order

The ISB proposed standards for defining joint coordinate systems of the upper limb are presented in Wu et al. (2005). These are the primary reference for the 3D upper limb model used in this research. Wu et al. (2005) established the bony landmarks used to define each segment and joint of the upper limb, their local coordinate systems (LCS) and a standard method of reporting joint and segment motion. Anatomical frames for both the proximal and distal segment forming the joint were used to define each joint coordinate system in addition to the joint rotation/decomposition order as recommended by the ISB (Kontaxis et al., 2009).

2.4.1.1 Humeral coordinate system definition

The humerus was defined by three points: the medial humeral epicondyle (EM), lateral humeral epicondyle (LM) and the GH joint rotation centre. Technically the GH joint rotation centre is not a bony landmark but it is required to define the longitudinal axis of the humerus. The ISB recommended its estimation via linear regression (Meskers et al., 1998a) or by calculating the pivot point of instantaneous helical axes of GH motions (Stokdijk et al., 2000). For this research, Meskers' approach was chosen. This method estimated the GH joint rotation centre from the relationship between scapula geometry parameters, calculated by a linear regression method. It was demonstrated by Meskers et al., (1998a) that a close relationship exists between the shape of the scapula and the factors that determine the position of the GH joint rotation centre i.e. the orientation of the glenoid and size of the humeral head. The 3D positions of five scapular bony landmarks were defined by LED markers. These landmarks were: the most dorsal point of the acromioclavicular joint; trigoneum spinae; angulus inferior; angulus acromialis and processus coracoideus. In its original paper this method resulted in a root mean square error (RMSE) of 2.32mm for the x-coordinate, 2.69mm for the y-coordinate and 3.04 for the z-coordinate (Meskers et al., 1998a). These errors were about 15% and 20% of intra and inter-subject variability.

While acknowledging its limitations, it was the most appropriate method due to the potential for reduced active ROM available in the OBPP group which would lead to inaccurate estimation using the instantaneous helical axes method.

Due to the relatively short distance between the EM and EL the effect of measurement errors, in particular on humeral AR (Zh axis), can be problematic (Veeger et al., 2003). Two options for defining the humeral coordinate system are recommended by the ISB (Wu et al., 2005). Option one uses the plane formed by EL, EM, and GH joint rotation centre pointing forward to estimate the Zh local coordinate axis. Option two uses the plane formed by the upper arm and the forearm (elbow flexed to 90º, forearm pronated) to estimate the same axis. The ISB recommended option two when the forearm was available for recording. As the forearm was recorded option two was used in this research. The position of the elbow as described above is critical to the accurate definition of the humeral coordinate system. When the elbow is flexed to 90º with full pronation, a more accurate calculation of the humeral coordinate system is possible. However, when the elbow is close to full extension its calculation becomes unreliable due to kinematic singularity i.e. the longitudinal axes of the humerus and the forearm are in near alignment (Schmidt et al., 1999). To account for this the static calibration was taken with the elbow in the required position, start and end positions for all tasks were with the hand resting palm down on ipsilateral knee with hips and knees at 90 to ensure a resting posture of elbow 90º flexion and full pronation. With the exception of the Abduction Task, all tasks demanded increased degrees of elbow flexion rather than extension thereby avoiding this position as much as possible. For the Abduction Task this limitation of the model was considered when interpreting data.

2.4.1.2 Rotation order for joint angle definition

Rotation orders for each joint and segment were chosen to ensure angles produced were as close as possible to clinical definitions of joint and segment motions. While acknowledging the importance of clinical interpretation in defining motion, differences as a consequence of mathematical calculations were unavoidable. Use of the ISB recommended sequence for GH joint motion has been shown to result in a gimbal lock effect especially at 0º and 180º humeral elevation in flexion and abduction (Šenk and Chèze, 2006). Gimbal lock is a mathematical in-determination of angle values dependent on sin B close to zero. As the joints approach 0º or 180º (Euler) or 90º or -90º (Cardan) there is an interruption of the resultant curve that does not correspond with clinical expectation e.g. curve jumps from positive 170º to -170º.

Several articles have explored alternative rotation sequences to reduce the incidence of gimbal lock while retaining clinical relevance of the resultant angles. Šenk and Chèze (2006) examined the clinical interpretation of the proposed ISB rotation sequence for GH joint (YXY). They found that the YXY sequence was convenient as long as movements did not go through a singular position (arm beside thorax) nor reach maximal ROM. This sequence is of particular interest when the movement is performed outside the anatomical plane, seen in all functional movements of daily living. Two rotation sequences, Euler (YXY)/Cardan (XZY), used to describe GH joint motion during abduction in scapular plane were compared by Phadke et al. (2011). They compared plane of elevation (POE) as described by first rotation axis in YXY and second in XZY; angle of elevation as in second rotation axis in YXY and first in XZY; AR as described by the third axis in both sequences. They found significant differences between the two sequences when describing positions of humeral POE, the magnitude of which was reduced at higher levels of humeral elevation. In the YXY sequence the humerus was significantly more anterior to plane of scapula, elevation angle was higher and the humerus was consistently more externally rotated. Two of their findings were that the YXY sequence was challenging to clinicians as the terminology was not common to clinical practice. The XZY sequence was better able to capture AR with arm by side of thorax in a more clinically meaningful manner. They concluded that there was no ideal way to capture GH motions through all ROM and planes. Alternative Euler decompositions of XZY when elevating the arm in the sagittal plane or ZXY when elevating in the scapular plane were recommended by Kontaxis et al. (2009). However, as the tasks analysed in this study were functional, not planar specific and no single rotation sequence has been identified to fulfil all requirements, the ISB recommendations were used to enable comparison of results with previous research.

2.4.2 Segment tracking

While the ISB recommended tracking of specific bony landmarks the method by which they are tracked was not specified. Therefore, a literature review of tracking methods was conducted to inform the most appropriate method for this research study. A description of the bony landmarks recommended to be tracked by the ISB is outlined in Table 2.1. The thorax, humerus, forearm and hand have defined bony landmarks which can be easily tracked either by direct skin markers or technical clusters.

Table 2.1: List of bony landmarks used to construct local anatomical coordinate systems Wu et al. (2005)

Bony landmarks	Description
Thorax	
C7: processus spinosus (spinous process) of 7th cervical vertebrae	Most dorsal point
T8: processus spinosus (spinous process) of 8th thoracic vertebrae	Most dorsal point
PX: processus xiphoideus (xiphoid process)	Most caudal point of sternum
IJ: incisura jugularis (suprasternal notch)	Deepest point
Clavicle	
S.SC: sternoclavicular joint	Most ventral point
S.AC: acromioclavicular joint	Most ventral point
Scapula	
AI: angulus inferior (inferior angle)	Most caudal point
AA: angulus acromialis (acromial angle)	Most laterodorsal point
PC: processus coracoideus (coracoid process)	Most ventral point
TS: trigonum spinae scapulae (root of scapular spine)	Midpoint of triangular surface on medial border of scapula in line with scapular spine
Humerus	
Cluster of 4 markers	Lateral aspect under deltoid insertion
GH: glenohumeral rotation centre	
EL: lateral epicondyle	Most caudal point of EL
ML: medial epicondyle	Most caudal point of ML
Forearm	
Cluster of 4 markers	2.5cm proximal to RS & US
US: Ulnar styloid	Most caudal and medial point of US
RS: Radial styloid	Most caudal and lateral point of RS
Hand	
MC3: styloid process of metacarpal 3	Most dorsal point on dorsal surface of hand
MCP2: metacarpophalangeal 2	Distal head
MCP3: metacarpophalangeal 3	Distal head
MCP5: metacarpophalangeal 5	Distal head

The scapula is the most difficult segment of the upper limb to track due to its shape, movement under the skin and lack of a fixed centre of rotation. However, exclusion of the ST joint severely limits the ability to understand shoulder function and every effort should be made for its inclusion (Veeger et al., 2003, Bolsterlee et al., 2013). The following section critically evaluates the various scapular measurement methods proposed in the literature. These included an invasive approach of pin insertion into the scapula (Karduna et al., 2001, McClure et al., 2001). While this is recognized as the most accurate, it is the least clinically applicable and was not feasible for this research. Several non-invasive methods using electromagnetic or optical tracking devices are identified in the literature. Based on critical evaluation, inappropriate methods were discarded and the most appropriate method adopted. A brief summary of the different non-invasive methods of scapular tracking explored in the literature is provided in Table 2.2.

Table 2.2: Non-invasive methods of three-dimensional scapular measurement

Method	Proposed by:	Comments
Scapulohumeral regression	de Groot and Brand (2001)	Not suitable for shoulder pathology
Scapular locator *(Palpation)*	Johnson et al. (1993); Meskers et al. (1998b); Barnett et al. (1999);Hébert et al. (2000)	Only suitable for static acquisition
Scapular tracker *(Palpation)*	Karduna et al. (2001); Prinold et al. (2011)	Capable of dynamic scapular tracking, only validated in adults with minimal further examination of its validity and reliability.
Inertial/magnetic sensors *(Dynamic)*	Cutti et al. (2008), Parel et al. (2012)	Capable of dynamic scapular tracking, valid and reliable in adults
Acromion method *(Dynamic)*	Karduna et al. (2001);Meskers et al. (2007);van Andel et al. (2009);Chu et al. (2012)	Valid up to 100º of humeral elevation, sensitive to plane of movement, replacement and calibration trials. Capable of tracking dynamic scapular movement, small & lightweight, which is important in young children
Surface mapping *(Dynamic)*	Mattson et al. (2012)	Capable of dynamic scapular tracking but only validated in healthy adults and recommended to record one movement in a clinical population; validated in static acquisition and for visibly prominent scapulae

2.4.2.1 Static scapular tracking

The palpation method of measuring scapular kinematics, using a variety of tracking devices, has been explored in the literature. However, the main aim of this study was to identify a valid, reliable and practical assessment method of 3D-ULMA of dynamic functional activities that could be used in participants with OBPP. This section briefly explores palpation as a method of assessing scapular kinematics. It concludes that despite the reported accuracy and reliability of this method, due to the static nature of data acquisition, it was not feasible for the purpose of this study.

Palpation has been identified as a powerful and accurate, within 2º of error, measure of scapular motion (de Groot, 1997). Palpation has been conducted using various methods briefly outlined below. The scapular locator (SL) method is the most validated method of quasi-static measurement of scapular movement, with agreement from experts in the field that it is the “silver” standard (Cutti and Veeger, 2009). It uses a specifically designed tripod mount manually placed on the scapula to locate the three scapular bony landmarks via palpation (Figure 2.1).

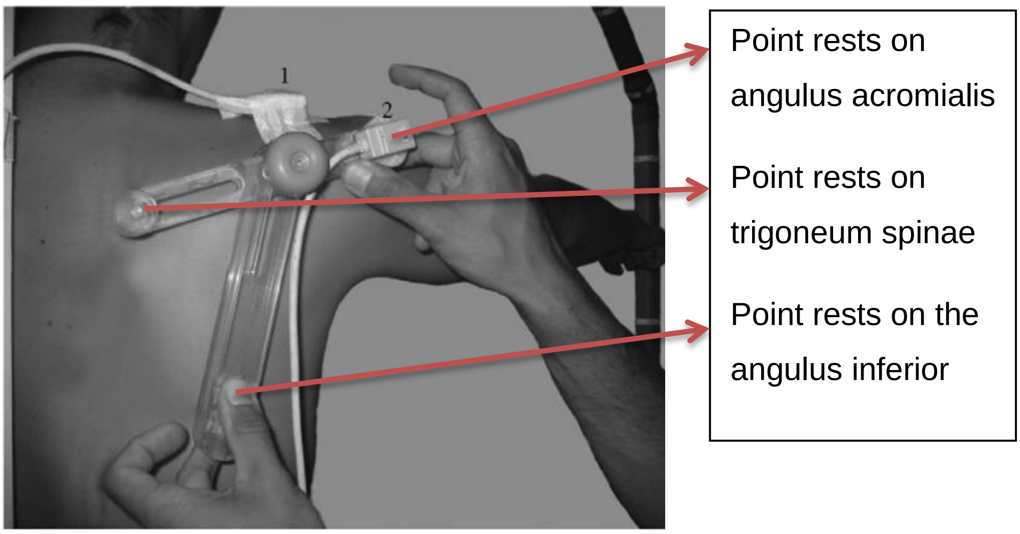


Image courtesy of Meskers et al., (2007).

Figure 2.1 Image of scapular locator

1/2 refer to magnetic receivers placed on the acromion and the scalular locator

It was initially described by Johnson et al. (1993) but further developed by Meskers et al. (1998b) to produce a complete shoulder kinematic data recording and processing methodology. Other static palpation methods include those by Barnett et al. (1999), who developed and tested the reliability of an alternative SL. It was proposed to have an improved leg design for repeatable positioning over defined scapular landmarks. They found the 95% confidence intervals (CI) for lateral rotation to be in the region of 3º-4º, an improvement on the 11º reported by Johnson et al. (1993). Finally the Optotrack probing system (OPS) for tracking scapular motion was validated by Hébert et al. (2000). This method used a probe attached to a rectangular rigid body with 6 infrared transmitters that defined the 3D spatial coordinates of the probe tip and, by extension, anything it touches. The OPS was found to have a mean difference of 1.73º (SD 2.2º) for individual scapular rotation, although this increased to 4.5º (SD 1.9º) for three combinations of scapular movement. The OPS intra-session reliability has been established in healthy adults and participants with shoulder impingement syndrome in three static positions with good to very good ICCs from 0.73 to 0.96 with 95% CI from 0.5 to 0.99 (Roy et al., 2007).

For any measure, it is important to establish its reliability in all forms and in different subject groups. Inter and intra-observer, intra and inter-session reliability of the palpation method have been established (Meskers et al., 1998b, Barnett et al., 1999, Hébert et al., 2000, Roy et al., 2007). However, most studies have used either healthy adults or adults with pathological shoulders. In addition, all of the studies cited have examined validity and reliability in specific planar movements such as scapular, coronal or sagittal and have not addressed functional movements.

2.4.2.1.1 Ability of static palpation to assess dynamic motion

Despite the lack of studies using the SL method in children or during functional movements, it has been used as the reference method in subsequent studies assessing the validity of dynamic tracking methods, assuming its validity and reliability within the participants. It was suggested by de Groot et al. (1998) that scapular motion was of a sufficiently slow speed to allow static measurement be generalised to dynamic movement or performance of functional tasks. However, these results are based on adults trained in performance of a specific task and cannot be generalised to children as children are not as developed in motor control and coordination (Petuskey et al., 2007, Coluccini et al., 2007). Furthermore, a study by Fayad et al. (2006) found that interpolation of statically recorded positions of bones cannot reflect scapular kinematics. They found that while protraction/retraction (P/R) and tilt were not significantly different between static and dynamic tasks lateral rotation was different. Ensuring children move at a specific submaximal speed and maintain static positions for re-palpation is not reflective of daily performance of functional tasks and its reliability is questioned.

Since each of the methods discussed above necessitate static palpation of bony landmarks, it remains that they cannot assess dynamic movement during functional activities. Static methods require reasonable compliance from participants to maintain their arm in the same position while re-palpation occurs. While each study states that, with practice and familiarity with the system, measurement speed was not an issue. All studies on static palpation have been completed on compliant adult subjects. The concern for this study is that children with OBPP would not be as tolerant or capable of maintaining static postures. Also, this research question proposed to examine the characteristics of movement patterns in children with OBPP during dynamic performance of functional tasks. Considering this, the established validity and reliability of static palpation did not outweigh the research goal. Therefore, it was concluded that the static measurement method could not adequately meet the research question posed in this study.

2.4.2.2 Dynamic scapular tracking

Clinicians are interested in the performance of dynamic functional tasks. The ability to distinguish the contribution of individual joints to each task is valuable in aiding management. Three-dimensional movement analysis can quantify these contributions and several methods have been explored in the literature.   These include inertial and magnetic sensors (Cutti et al., 2008), surface mapping (Mattson et al., 2012) scapular tracker and acromion method (AM) (Karduna et al., 2001, McQuade and Smidt, 1998). The AM is the most researched method of dynamic scapular tracking with established validity and reliability in both TDC and children with hemiplegic cerebral palsy (HCP). It was considered to be the most appropriate method for the purpose of this research. In the following section, a brief outline of other methods is provided before an in-depth analysis of the AM.

2.4.2.2.1 Inertial and magnetic sensors

This is a non-invasive technique proposed by Cutti et al. (2008) based on an Inertial and Magnetic Measurement system (IMMS, Xsens Technologies, NL). The scapula is tracked by an MTx sensor (Xsens Technologies, NL) placed on the skin, just above the scapular spine. Each MTx is a small lightweight box containing a 3D-gyroscope, accelerometer and magnetometer, which provide the orientation of the technical coordinate system of the MTx relative to the global coordinate system (GCS). Using these sensors the problem of marker occlusion is negated as the sensor can be constantly “seen”. Preliminary studies have confirmed this method’s validity and reliability in measuring upper limb kinematics in healthy and adults with pathology (Cutti et al., 2008, Parel et al., 2012). However, it has not yet been explored in children and therefore, was not appropriate for use in this research

2.4.2.2.2 Scapular mapping

Scapular mapping is a more recent method described by Mattson et al. (2012). It applies elastic tape, covered with 300 6mm two dimensional (2D) circular dots with 12mm centre to centre placing, over the surface of the scapula. This allows measurement of scapular orientation by analysing the deformation of the overlying soft tissue (Figure 2.2).

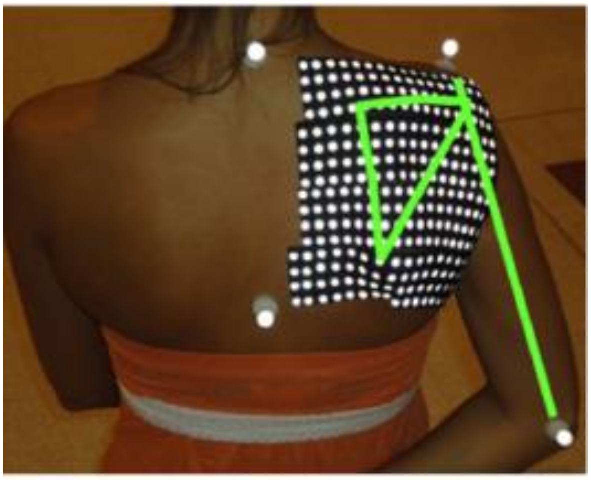


Image adapted from Mattson et al., 2012.

Figure 2.2: Scapular mapping with superimposed scapula and humerus.

It was validated as a 3D scapular measurement tool but only in normal adults during static data acquisition (Mattson et al., 2012). They found a maximum mean error of 3.8º and root mean square error (RMSE) of 5.9º in ST lateral rotation in the Hand-to-Neck position. These errors are smaller than those found in AM studies: RMSE 11.4º (Karduna et al., 2001); RMSE 13º (Meskers et al., 2007) RMSE 8.4º(van Andel et al., 2009). However, these results were based on measurement of scapular orientation during dynamic movement and, as such, are not directly comparable. Another limitation of this method is that it is only applicable to visibly prominent scapulae. This method requires validation in measuring dynamic movement and specifically in children. Consequently, it was not appropriate for this research question.

2.4.2.2.3 Scapular tracker

The scapular tracker method was validated in healthy adults by Karduna et al. (2001) against the reference standard of bone pin insertion. This comprised a custom designed device, which holds a magnetic tracking receiver (Polhemus 3Space Fastrak, Colchester, VT), that follows scapular orientation during movement. The base of the tracker holds the receiver and remains attached along the length of the scapular spine. The footpad is located at the end of an adjustable arm and is positioned against the posterior-lateral acromion (Figure 2.3).

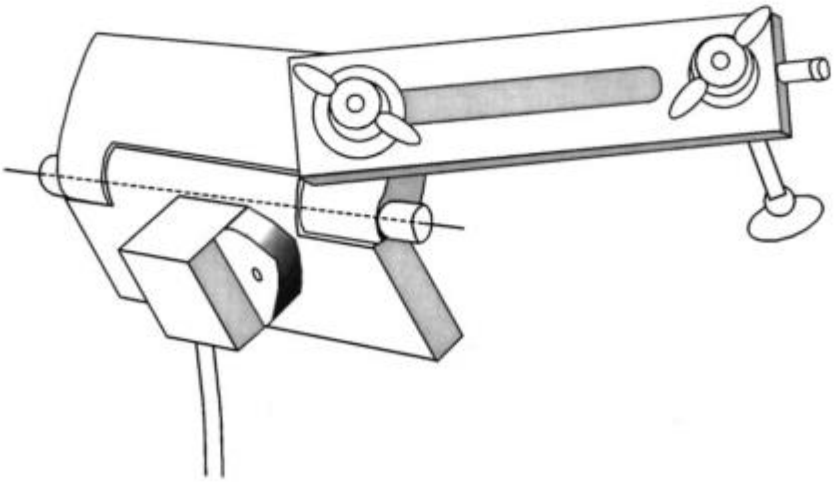


Image adapted from Karduna et al., (2001)

Figure 2.3: Scapular tracker,

Karduna's results showed that the scapular tracker method demonstrated reasonable accuracy for assessing a variety of motions below 120º of TH elevation, with errors being attributed to skin motion artefact. The scapular tracker method had lower RMSE for scapular posterior tilt (4.7º) and external rotation (3.2º) but larger for upward rotation (8.0º). While validity was established in this study and confirmed in a later study (Prinold et al., 2011) no studies have examined its validity or reliability in children. For these reasons, adoption of this method was not explored further.

2.4.2.2.4 Acromion method

The AM is the most researched method of dynamic scapular tracking. It was first described by McQuade and Smidt (1998) and Ludewig and Cook (2000). A marker is attached to the broad, flat surface of the posterior-lateral acromion and calibrated within the anatomical scapular frame (Figure 2.4). This marker can either be an electromagnetic sensor or a cluster of markers capable of being tracked by a 3D motion analysis system such as Codamotion (Charnwood Dynamics Ltd, Leicestershire) as used in Central Remedial Clinic (CRC).

Figure 2.4: Acromion Method

Having explored the literature it was concluded that the AM, being the most validated method of measuring dynamic movement in children and pathological populations, was the most feasible within the laboratory set-up. The following section discusses the literature establishing validity and reliability of the AM in measuring 3D scapular motion.

2.4.2.2.4.1 Validity of the acromion method

Validity of the AM using a variety of markers and tracking systems has been investigated in several studies. Scapular kinematic data measured by a receiver attached to the flat surface of the posterior-lateral acromion and tracked using an electromagnetic system (Polhemus 3 Space Fastrak, Colchester, VT) was validated in healthy adults (n=8) by Karduna et al. (2001), using bone pin insertion as the reference method. Its validity was further investigated by Meskers et al. (2007) using the SL as the reference method, referred to as the "tripod method" in this study. Both concluded that the AM demonstrated reasonable accuracy for a wide variety of scapular motion during humeral elevation below 120º.

Over the entire ROM Karduna et al. (2001) recorded a RMSE of 6.3º for upward rotation, reduced to 2º when an upward rotation correction factor was applied, 6.6º for posterior tilt and 9.4º for external rotation. Meskers et al. (2007) reported a maximum difference between the AM and "tripod method" of 9º of external rotation during abduction and 6º of protraction during forward flexion. The low inter-trial RMSEs of the AM indicated high reproducibility. It had an intra-observer RMSE of 5º, with this error reduced to 2º by applying a linear regression model. The difference between the “tripod method” and AM ranged from 3º-6º in all scapular movements in the sagittal and frontal plane of humeral elevation. As found by Karduna et al. (2001), the mean error between the methods was higher beyond 100º of humeral elevation. This was due to the ability of the pins and “tripod method” to change position while the AM was fixed. This is a limitation of dynamic tracking methods caused by deviation of the technical and anatomical coordinate systems from each other due to muscle bulk and soft tissue deformation as the arm elevates (van Andel et al., 2009, Brochard et al., 2011, Prinold et al., 2011).

In contrast to the electromagnetic system outlined above, this research proposed to track a specifically designed acromion cluster (AC) using an optoelectronic system   Two studies investigated the validity of an AC in measuring scapular kinematics while being tracked by optoelectronic systems (van Andel et al., 2009, Chu et al., 2012). Both clusters were similar in design and consisted of 3 markers spaced at a sufficient distance to avoid axis cross over or “crosstalk” and create a technical coordinate system. Different reference methods were used by both studies. The SL was used as the reference method by van Andel et al. (2009), while Chu et al. (2012) used the reference measure of Dynamic Stereo X-ray. Dynamic Stereo X-ray provides direct, high accuracy measurements of bone motion (Bey et al., 2006).

With a maximal mean difference of 8.4º over the entire ROM, van Andel et al. (2009) concurred with previous studies that no significant difference existed between the two methods except for external rotation during abduction (ANOVA for repeated measures 0.021 $p<0.05$). Overall, they found that the AC generally underestimated scapular movement except for: ST anterior/posterior (A/P) tilt in 90º of abduction; protraction and external rotation in forward flexion. Calculated errors of scapular kinematics found by Chu et al. (2012) were within the range of previous studies (Karduna et al., 2001, Meskers et al., 2007). While there was a high correlation ($r = 0.412$-0.98) between the Dynamic Stereo X-ray and

AC method for most scapular movements, AC method demonstrated limitations in tracking scapular A/P tilt during arm elevation in muscular bodies and only showed a moderate correlation in scapular P/R during internal/external rotation at 90º. It was also noted that, similar to Karduna et al. (2001) and Meskers et al. (2007), the AC method underestimated ST medial/lateral (M/L) rotation by ~14º, most likely explained by skin motion artefact. It was concluded that, due to the high correlations, AC method appropriately tracks scapular movement but underestimates ROM.

All studies already discussed have examined elevation movements in different planes. Warner et al. (2012) examined AC validity in healthy adults measuring scapular kinematics in the lowering phase of elevation. They found no significant difference for sagittal or scapular plane movements between SL and AC. In the frontal plane, upward rotation was significantly underestimated and posterior tilt overestimated. However, these errors were within ranges previously reported concluding that the AC was as accurate during the lower phase of elevation.

All studies concluded that caution was needed in interpreting measures at higher levels of humeral elevation. However, since most functional movements are under 100º it was considered valid to use the AC to measure activities of daily living (Magermans et al., 2005). Given the choice, the SL was considered the best option for non-invasive evaluation of scapular motion (van Andel et al., 2009). However, as it does not allow assessment of unconstrained dynamic movement patterns it did not fit the purpose of this study. A limitation inherent in all validity studies was that the most commonly used reference measure, SL, has an existing 2º palpation error (de Groot, 1997) which compromises accuracy. Bone pin insertion, fluoroscopy or dynamic x-ray are more reliable alternative reference measures but are not as accessible in all settings.

Considering this limitation and based on evaluation of the research it was concluded that the AM is a valid measurement method of tracking scapular kinematics with known limitations. It is the most appropriate method for the purpose of this research and data interpretation acknowledges existing limitations.

2.4.2.2.4.2 Reliability of the acromion method

Both intra and inter-session, inter and intra-observer reliability of the AM have been examined in the literature in a variety of populations (Meskers et al., 2007, van Andel et al., 2009, Jaspers et al., 2011b, Jaspers et al., 2011c, Brochard et al., 2011, Lempereur et al., 2012, Roren et al., 2013, Vanezis et al., 2015). While its reliability has been established, its robustness varies with scapular rotation examined, POE and number of observers. Specific scapular rotations have not been consistently reported to be reliable in all movements assessed.

AM reliability has been assessed in normal adults with the following results. Intra-session reliability of the AM in measuring scapular rotations during planar and functional movements, while dependent on plane of movement and rotation assessed, was good to excellent with ICC values either reported to be >0.80 (Meskers et al., 2007, Lempereur et al., 2012) or between 0.63-0.92 (van Andel et al., 2009, Brochard et al., 2011). The reliability of ST A/P tilt was questioned by van Andel et al. (2009) with low ICCs (0.29-0.59) though this was not seen in other studies. They found ST A/P tilt to have a maximum error of 8.4º which was equal to mean maximum error in the validation study suggesting that ST A/P tilt could not be reported reliably.

As with any measurement tool methodological sources of error, such as different observers/palpation accuracy, decrease reliability. However, intra-session, intra-observer reliability of the AM in adults was found to be good to excellent ICC >0.76 for all scapular rotations during planar movements and hair combing except for scapular P/R during back washing (ICC 0.64) (Roren et al., 2013). Inter-session, inter-observer reliability was lower with reported ICCs between 0.35-0.92, scapular P/R recording the lowest ICCs (0.39-0.73). Tasks of ADL had lower ICC values (0.38-0.89) suggesting AM reliability depends on selected tasks. Further investigation of reliability of AM in specific populations is necessary to support its clinical use in assessing impact of interventions and change over time.

2.4.2.2.4.3 Marker position on acromion and arm position for calibration

Consensus is lacking on both marker position on the acromion and arm position for calibration due to their influence on measurement accuracy and potential source of methodological error. In the presence of increased error recorded on replacement of the acromial receiver, Meskers et al. (2007) recommended a static calibration of the acromion receiver during each recorded session to define the orientation of the technical coordinate systems. Most studies used a single static neutral calibration position of "arm by side". Due to skin motion artefact and muscle bulk this contributed to the reduced accuracy of AM in ROM >100º humeral elevation(van Andel et al., 2009).

Using the SL as a reference method, three positions of the AC placement and different calibration angles in adult participants were investigated by Shaheen et al. (2011) during humeral elevation in the scapular plane. Two positions had been described previously; A - anterior edge of acromion (Matsui et al., 2006); B – most posterior-lateral part of acromion (Karduna et al., 2001, Meskers et al., 2007, van Andel et al., 2009) and a previously undocumented C – meeting point of acromion and scapular spine. Position C combined with a calibration angle of 90º of humeral elevation had the lowest RMSE (3-5º) and was half the RMSE (6-10º) of Position B with neutral calibration position. While these results highlighted the importance of choosing the correct attachment and calibration position for tasks being analysed, it was acknowledged that error was associated with the chosen reference measure and results should be interpreted in this light.

The accuracy of Position C in measuring scapular kinematics in combination with different calibration positions (30º, 60º, 90º 120º, multiple) was further investigated by Prinold et al. (2011). It concurred with Shaheen et al. (2011), finding smaller RMSE for upward rotation and internal rotation with the AM compared with previous research (Karduna et al., 2001), though posterior tilt was overestimated. Altering the calibration position changes errors and reduces the mean error, distributing it more evenly over the full ROM. The optimal single calibration (SC) position was found to be at 90º humeral elevation. Double calibration (DC), first with "arm by side" and second with "arm in maximum humeral elevation", was compared with a SC of "arm by side" examined by Brochard et al. (2011). The RMSEs of DC were lower for all rotations tested and ranged from 2.96º to 4.48º for DC and from 6º to 9.19º for SC. Inter-trial reliability was good to excellent for both SC (0.75-0.96) and DC (0.63-0.92). Inter-session reliability was moderate to excellent for SC (0.56-0.92) and moderate to good for DC (0.49-0.78) which suggested the introduction of methodological replacement error.

Despite the reduced error using alternative position C and multiple calibrations, it was decided to continue using the previously investigated position B with static calibration with "arm by side". This decision was based on two arguments. Firstly, the reliability of varied calibrations with the alternative position C for the AC has not been established. Secondly, based on expert clinical knowledge not all participants with OBPP would achieve 90º of abduction. This would limit consistent implementation of the reliability protocol. The SC method preserved repeatability ensuring the AC can be reliably used in a clinical setting for repeated measurements. It was accepted that movement accuracy above 100º would be reduced and data were interpreted with respect to this fact.

2.4.2.2.4.4 Acromion method in paediatric populations

As stated already the AM is the most investigated method in the literature with studies examining its use in TDC, children with HCP and OBPP (Jaspers et al., 2011b, Jaspers et al., 2011c, Lempereur et al., 2012, Nicholson et al., 2014). Validity and reliability of AM have been established in TDC and HCP with due attention given to methodological considerations. Reliability of the AM in children with OBPP has not been assessed. One study by Nicholson et al. (2014), suggested poor validity in the OBPP population. The limitations of this study are discussed later in this section.

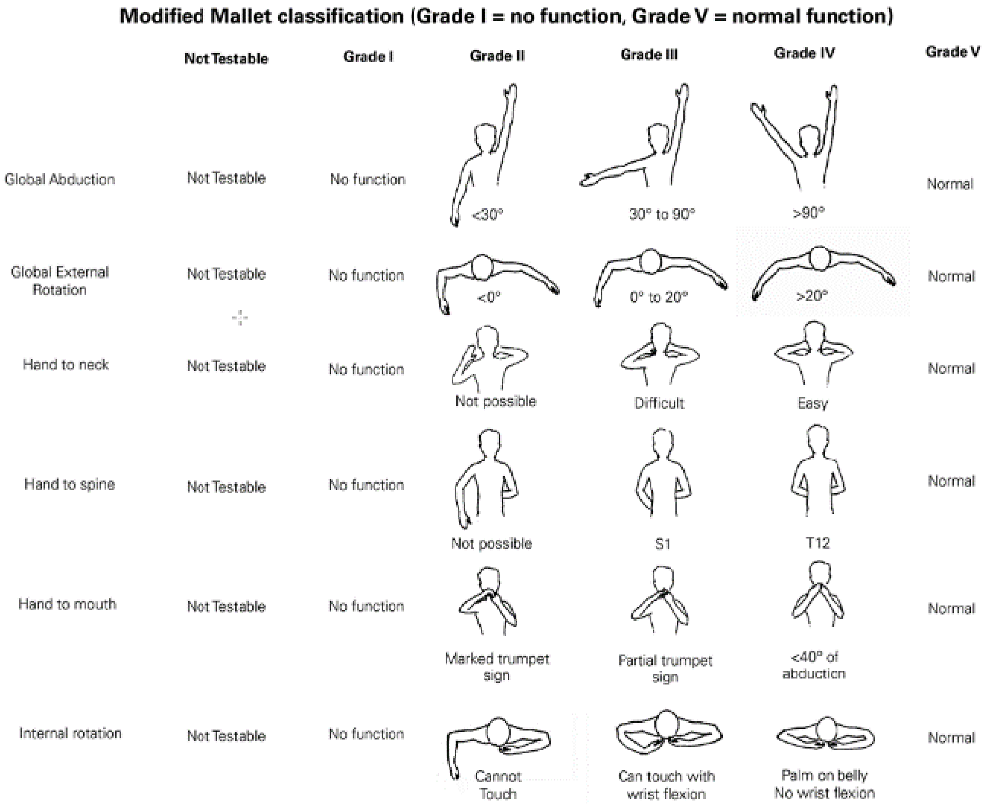
In investigating the validity of the AM in TDC and children with HCP, using the SL as a reference method, Lempereur et al. (2012) found no significant difference between the methods for 4/6 axes of scapular rotation. However, in TDC during abduction the AM significantly underestimated protraction (RMSE 9.6º) and overestimated posterior tilt (RMSE 6.52º). In HCP during flexion, lateral rotation (RMSE: 5.23º) and protraction (RMSE: 7.69º) were significantly underestimated by the AM. It was acknowledged that concurrent validity was limited as palpation has its own error of 2º and that inherent problems exist with rigid body segmental modelling. They concluded that the AM can discriminate differences within a clinical setting, the main purpose of such motion analysis.

With established validity in these two populations reliability of the AM was also explored. Inter and intra-session reliability of kinematic waveforms and angle at PTA have been established in TDC and children with HCP (Jaspers et al., 2011b, Jaspers et al., 2011c, Lempereur et al., 2012, Vanezis et al., 2015). Lower reliability coefficients for inter-session findings compared with intra-session (ICC 0.1-0.5; ICC >0.6 respectively at PTA) highlighted that methodological issues most likely contributed to error e.g. marker placement, palpation, joint centre calculation (Jaspers et al., 2011c). Despite differences in methodology, functional method used instead of regression method to estimate GH joint centre and elbow F/E , kinematic waveforms were found to have good intra and inter-error values, between 1.0º to 4.1º and 1.6º to 5.1º with the lowest consistently seen in scapular A/P tilt (Jaspers et al., 2011b, Vanezis et al., 2015). Reliability was better in HCP with good repeatability for intra-session (ICC >0.70) and inter-session (ICC >0.60) at PTA, except for P/R (ICC >0.50) in reach to grasp vertically (Jaspers et al., 2011b). It was concluded that scapular rotations can be measured reliably in HCP with measurement errors <5º for A/P tilt and M/L and 5-8º for P/R (Jaspers et al., 2011b). Similarity of waveforms was evident for all scapular rotations in both intra and inter-session (Correlation of Multiple Coefficients >0.80) during reach and reach to grasp tasks, although lower recordings were found in scapular A/P tilt in Hand-to-Mouth and Hand-to-Spine (CMC >0.50-0.70) and P/R in Hand-to-

Mouth (Correlation of Multiple Coefficients >0.50) (Jaspers et al., 2011b). This supported previous findings that protraction measurement depends on the exact position of the acromial marker (Meskers et al., 2007, van Andel et al., 2009).

Reliability was dependent on the type of task performed. Lower reliability has been found during functional tasks compared with planar movements (Lempereur et al., 2012) and more refined movements (forearm pronation/supination (P/S)) compared with gross movements (TH elevation) (Vanezis et al., 2015). It has also been noted that while a larger ROM produced larger absolute values of measurement error the relative error values were lower (Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). This highlighted that when interpreting results the magnitude of ROM should be considered. There was greater difficulty ascertaining acceptable reliability in joints with much smaller ROM. These were important considerations for methodology requiring tight control of testing conditions and being cognizant of potential unreliability in certain planes and ROM.

To our knowledge, only one study has examined the validity of the AM in measuring non-planar scapular movements in children with OBPP (Nicholson et al., 2014). This paper was valuable in developing the research question of this study and aided the interpretation of its results. In this study the measurements of the AM were compared to manual palpation in ten participants with OBPP, in neutral and six different modified mallet positions (Figure 2.5).



Adapted from Abzug et al. (2010)

Figure 2.5: Modified Mallet scale

Based on clinical expertise they determined that an error of >10º indicated measurement inaccuracy. While errors in measurement using the AM were found, smallest in Hand-to-Spine and largest in Hand-to-Neck Tasks, the only significant difference between palpation and AM was in total rotation in the Hand-to-Neck Task. They concluded that the AM was not a valid measurement tool for the OBPP population. However, on further examination of the results of individual axes and movements, RMSE recorded for some rotations and movements were within acceptable limits of error (Table 2.3).

Table 2.3: Root mean square error between palpation and AM

Units of measurement – degrees; Up/Down – upward/downward rotation; Int/Ext – internal/external rotation; A/P – anterior/posterior tilt

Adapted from (Nicholson et al., 2014)

Rotation	Abduction	External Rotation	Internal Rotation	Hand to Mouth	Hand to Neck	Hand to Spine
X (Up/Down)	12.7	10.2	5.2	16.2	8.5	8.5
Y (Int/Ext)	8.6	7.3	5.9	11.6	8.5	8.5
Z(A/P)	5.2	6.5	5.2	8.5	6.8	6.8

In general, RMSE of the X axis (upward/downward rotation) had the lowest validity with 3 tasks having an error >10º. All other rotations, except for internal/external rotation in Hand-to-Mouth Task, were <9º. Mean relative errors of total rotation were presented to conclude the poor validity of the AM. However, this measure is heavily confounded by actual movement amplitude and over-estimates the error in segments that do not have large amplitude. In a systematic review of repeatability of kinematic data, McGinley et al. (2009) recommended using absolute measure of repeatability, such as the SEM, rather than relative measures. Based on the absolute RMSE values reported by Nicholson et al. (2014) the AM was within acceptable limits for scapular A/P tilt and internal/external rotation in all tasks except Hand- to-Mouth for internal/external rotation; all rotation axes for the Internal Rotation Task and up/downward rotation for Hand-to-Neck and Hand-to-Spine Tasks. Therefore, interpretation of RMSE indicated that the AM has potential as a measurement tool once its true repeatability is known, as clinical validity cannot be fully assessed based on relative error alone.

Validity and reliability are different constructs, reliability being a sub construct of validity. Therefore, each should be established for any measure to ascertain its robustness. It is acknowledged that rigid body segmental modelling has inherent errors in its attempts to replicate human movement. A recent systematic literature review concluded that the AM was the most valid method of measuring of dynamic scapular movement

(Lempereur et al., 2014). Yet caution was advised by the findings of Nicholson et al. (2014) for its use in children with OBPP. A method that reliably measures movement can be used to assess change. To our knowledge, the reliability of the AM in measuring scapular movement in children with OBPP has not been explored. Therefore, the AM was selected as the best available clinical method of evaluation to satisfy the purpose of the research question in light of its established reliability and validity of in the literature. However, it was acknowledged that its robustness varies with methodological considerations.

2.5 Implementation of 3D-ULMA in the research laboratory

The Gait Laboratory at the CRC is fully equipped with 4 CODA cx1 optical scanners (Codamotion, Charnwood Dynamics Ltd.). This is an optoelectronic tracking system that uses miniature infra-red active markers (LED)**,** each with its own unique identity, to track the key positions on any participant. Signals from these active markers are beamed to CODA sensor units**.** Three masked linear arrays in each CODA unit combine to measure X, Y and Z coordinates of each active marker, providing an immediate and precise 3D measurement in real time.

2.5.1 Development of the CODA upper limb model

The technical support team at Codamotion developed an upper limb model, based on ISB recommendations using a specifically designed AC, modelled on the cluster used by van Andel et al. (2009), to track scapular kinematics using a software package (ODIN) for data collection (Figure 2.6). This cluster was a small, rigid mount with three arms holding markers. Three markers were positioned in series with the fourth perpendicular to the middle maker. The marker at the midpoint of the straight arm defines the acromioclavicular joint. This mount can be feasibly placed on small scapulae. It is made of lightweight plastic with a small circular base attached to the acromion via double sided sticky tape. It does not restrict movement. The anatomical bony landmarks, cluster positions, and virtual landmarks are outlined in Table 2.4. The ODIN protocol “CDLUpperArm – Shoulder (predictive method) – 1.03 – Acromion Cluster” enabled calibration of the AC’s technical coordinate frame and defined its orientation with regard to the scapular anatomical coordinate frame.

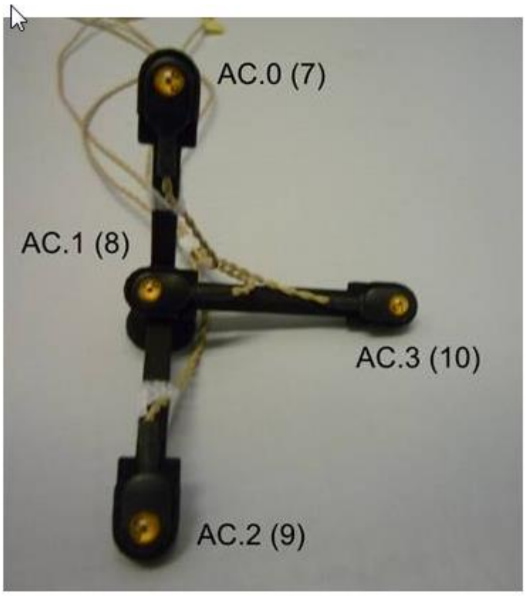


Figure 2.6*: Acromion cluster mount designed for this research*

AC – Acromion cluster

Due to the small size of children’s shoulders and the positioning of the AC, the acromioclavicular (S.AC) joint landmark was no longer accessible. Consequently, the acromioclavicular joint was defined as the base of the cluster. The markers attached to the AC have a specific order, described in Figure 2.6. The correct application of this order was imperative to enable accurate calculation of the S.AC joint.

Table 2.4: List of bony landmarks used to construct local anatomical coordinate systems and tracking method

LED - Light emitting diode

Bony landmarks	Description	Tracking
Thorax		
C7: processus spinousus (spinous process) of 7th cervical vertebrae	Most dorsal point	1. Active LED
T8: processus spinousus (spinous process) of 8th thoracic vertebrae	Most dorsal point	2. Active LED
PX: processus xiphoideus (xiphoid process)	Most caudal point of sternum	3. Active LED
IJ: incisura jugularis (suprasternal notch)	Deepest point	4. Active LED
Clavicle		
S.SC: sternoclavicular joint	Most ventral point	5. Active LED
S.AC: acromioclavicular joint	-	6. Base of cluster
Scapula		
AI: angulus inferior (inferior angle)	Most caudal point	23. Active LED
AA: angulus acromialis (acromial		24. Active LED
angle)	Most laterodorsal point	25. Active LED
PC: processus coracoideus		26.Active LED
(coracoid process)	Most ventral point	
TS: trigonum spinae scapulae		**Only recorded for static acquisition**
	Medial scapular border in line with scapular spine	
Acromion Cluster		
AC.0	Bottom arm of the cluster is placed on the flat,	7. Active LED
AC.1	posterior-lateral surface of the acromion	8. Active LED
AC.2		9. Active LED
AC.3		10. Active LED

Bony landmarks	Description	Tracking
Humerus		
Cluster of 4 markers	Lateral aspect under deltoid insertion	11-14. Active LED
GH: glenohumeral rotation centre		Estimated by Meskers' linear regression
EL: lateral epicondyle	Most caudal point of EL	Pointer acquisition
ML: medial epicondyle	Most caudal point of ML	Pointer acquisition
Forearm		
Cluster of 4 markers	1inch distal to RS & US	15-18 Active LED
US: Ulnar styloid	Most caudal and medial point of US	Pointer acquisition
RS: Radial styloid	Most caudal and lateral point of RS	Pointer acquisition
Hand		
MC3: styloid process of metacarpal 3	Most dorsal point on dorsal surface of hand	19. Active LED
MCP2: metacarpophalangeal 2	Distal head	20. Active LED
MCP3: metacarpophalangeal 3	Distal head	21. Active LED
MCP5: metacarpophalangeal 5	Distal head	22. Active LED

2.5.1.1 Face validity of the acromion cluster

During pilot testing on a healthy adult, concerns identified in the literature with regard to the accuracy of skin markers in tracking dynamic scapular movement were confirmed. This opinion was based on visual observation and re-palpation of scapular landmarks at movement end. The LED was placed on the angulus inferior when the arm was in a resting position of palm face down on ipsilateral knee. The black skin mark indicated the palpated position of the angulus inferior at the end of the abduction movement (Figure 2.7). This demonstrated the inaccuracy of the skin markers in following scapular movement, further confirming the argument that the AC was appropriate to answer the research question.

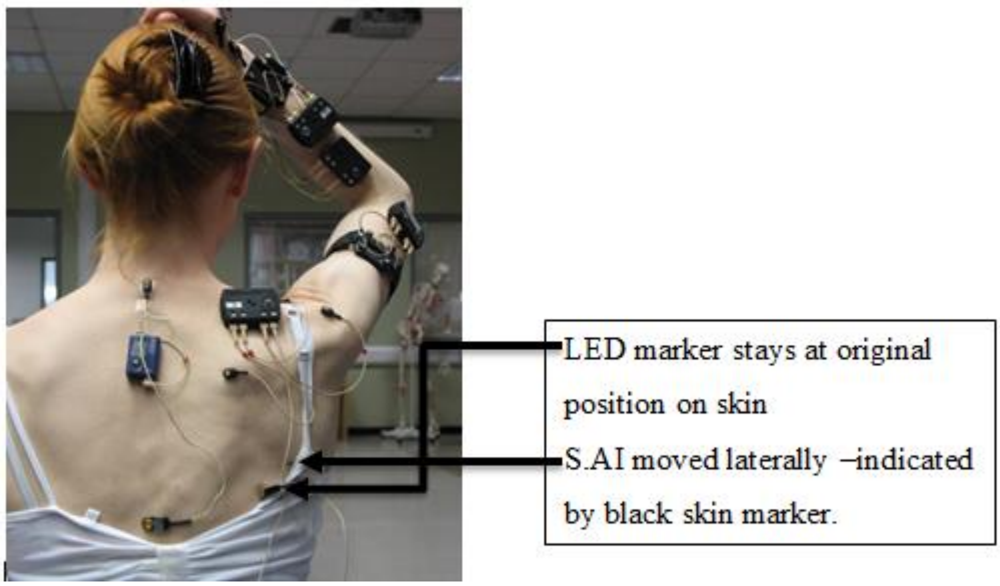


Figure 2.7*: Marker set up with smaller upper arm cluster, demonstrating the inaccuracy of the angulus inferior skin marker in following scapular movement*

LED – Light emitting diode; S.AI – Scapular angulus inferior

A visual improvement in dynamic scapular tracking was evident on observation of the real time stick figure at completion of the Abduction Task (Figure 2.8). This established face validity of the AM. More extensive validation of this method was beyond the scope of this research. Based on a comprehensive literature review, sound clinical reasoning and the absence of a gold standard that can be applied in a clinical setting the primary investigator was satisfied by this visual observation that the AM was the most appropriate method to investigate the aims of this research.

On visual inspection, the thorax and hand skin markers accurately recorded segment movement and, due to practical constraints, clusters were not specifically developed for this research study.

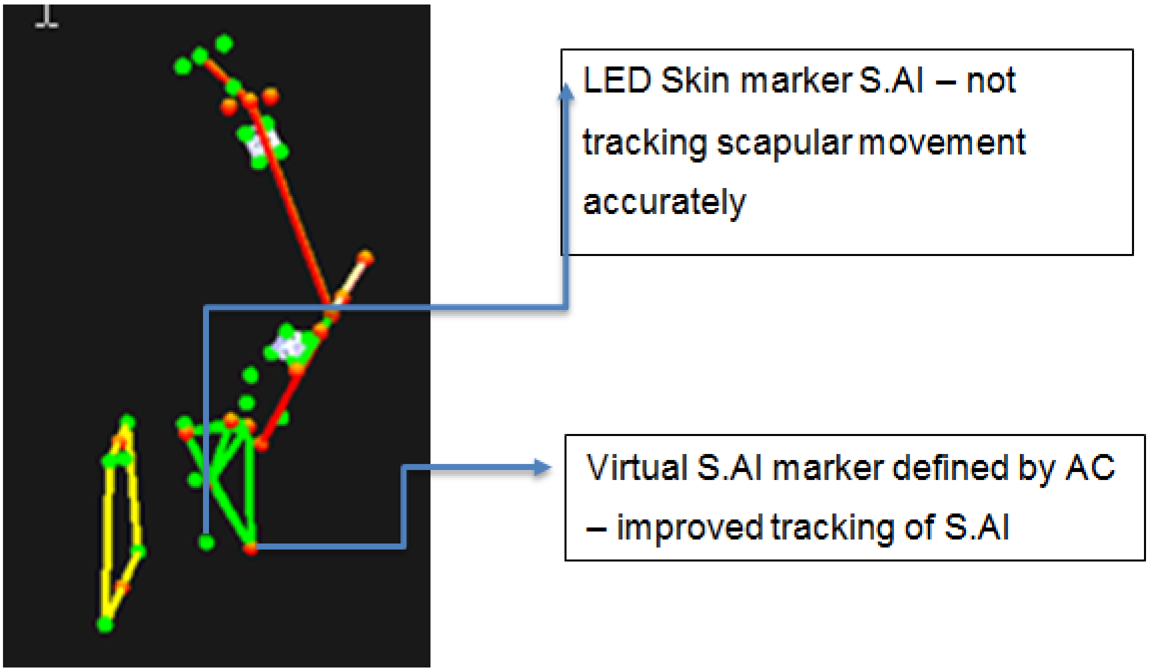


Figure 2.8: Stick figure of global abduction

LED: Light emiting diode; S.AI: Scapula angulus inferior; AC: Acromion cluster

2.5.2 Final marker set up

The final marker set up for this study followed ISB recommendations (Wu et al., 2005) using an AC to track the scapula (van Andel et al., 2009, Jaspers et al., 2011c, Lempereur et al., 2014) via an optoelectronic tracking system. Table 2.5 details the differences between the van Andel et al. (2009) and CODA upper limb models, while Figure 2.9 shows final set-up of the upper limb model on a typically developing child.

Table 2.5: Comparison between CODA and van Andel et al. (2009) upper limb models

C- Cervical process; PX: Processus xiphoideus; IJ- Incisura jugularis; LED- Light emitting diode; MC – Metacarpal; MCP Metacarpal phalangeal

Segment	Location: van Andel (2009)	Tracking: van Andel (2009)	Location: CODA	Tracking: CODA
Thorax	Sternum	Cluster, 3markers	C7, T8, PX, IJ	LED surface skin markers
Acromion	Flat, posterior-lateral aspect	Cluster, 3markers	Flat, posterio-lateral aspect	Cluster, 4markers
Upper arm	Lateral aspect under deltoid insertion	Cluster, 3markers	Lateral aspect under deltoid insertion	Cluster, 4markers
Forearm	Proximal to radial & ulnar styloid	Cluster, 3markers	~1inch proximal radial & ulnar styloid	Cluster, 4markers
Hand	Dorsal surface	Cluster, 3markers	MC3, MCP2, MCP3, MCP5	LED surface skin markers

Figure 2.9: Final upper limb set up on a typically developing child

2.5.3 Calibration and pointer acquisition

Calibration of any skin fixed measure for axis definition at every recording session was essential to minimise measurement error. Once all markers and clusters were placed on the participant, pointer acquisition established the virtual landmarks of humeral lateral epicondyle (EL), humeral medial epicondyle (EM), radial styloid (RS) and ulnar styloid (US). As discussed in section 2.4.2.2.4.3, both placement of the AC and arm position for calibration influenced measurement accuracy. The practical consideration of each child with OBPP being able to achieve 90º of elevation for calibration limited the implementation of this recommended calibration position in this study (Shaheen et al., 2011). Therefore, a single neutral calibration position as recommended by the ISB and used in previous studies (Karduna et al., 2001, van Andel et al., 2009, Meskers et al., 2007) was adopted with caution advised with measures above 100º (van Andel et al., 2009). This was considered appropriate as a study by Duff et al. (2007) demonstrated that functional tasks did not necessarily use >100º elevation and not all children with OBPP function in this ROM.

The neutral, static calibration position was defined as: participant sits with hips and knees at 90º, resting their hand, palm down, on ipsilateral knee. In this position the arm is by the side, elbow flexed and forearm pronated. The actual degree of elbow flexion was not specified but it was as close to 90º as possible as recommended by the ISB. During the static calibration test the position of all markers was recorded. This permitted definition of both the GH joint rotation centre via a linear regression equation (Meskers et al., 1998a) and the relationship between the technical and anatomical coordinate system.

Once the static acquisition for calibration was taken, the angulus inferior, angulus acromialis, processus coracoideus, trigoneum scapulae markers (Table 2.4) could be removed from the participant as they were not tracked. As their presence did not interfere with marker view it was decided to leave them on the participant until the end of the session to minimise interference with the model or disturb the participant just prior to recording data.

Once satisfied with UL model and laboratory set up, a final testing session was completed on a ten year old typically developing child. This identified a problem of marker occlusion especially with the anterior thorax markers in the Hand-to-Mouth and forearm markers in the Hand-to-Spine Tasks. It was accepted that both were a limitation of using anterior markers instead of a thorax cluster when performing tasks that necessitated the arm approaching the anterior aspect of the thorax and orientation of the forearm in the Hand-to-Spine Task. It was not feasible to have more cameras to aid marker view or integrate a thorax cluster within the time frame of this research study therefore; it was decided to continue with the current set up, acknowledging its limitations.

Chapter 3 Methods

This chapter will provide details of study design, participant selection and data acquisition. Tasks selected for analysis and data collection will be outlined. Finally, the framework for data analysis will be explained.

3.1 Study design

This was a case control study using 3D-ULMA. The first aim of the study was to examine movement pattern characteristics that differentiated between TDC and children with OBPP while performing activities of the modified Mallet Scale (Abzug et al., 2010). It was therefore a quantitative, observational, cross-sectional study.

The second aim was to perform a test-retest reliability assessment of the model's ability to reliably record the movement patterns of children with OPBP. Each child with OBPP was reassessed within a designated time period by the same assessor using the same marker protocol. All observations were compared using statistical analysis to estimate components of measurement error.

The hypotheses were that:

- The chosen model of 3D-ULMA would measure dynamic movement within an acceptable error of measurement.
- Children with OBPP would have faster arm movements.
- Children with OBPP would use more scapular movement to achieve functional tasks.
- Children with OBPP would be biased towards shoulder internal rotation compared with TDC.

3.2 Participants

3.2.1 Ethical approval

Ethical approval was sought from and granted by the CRC Scientific and Research Trust Ethics committee in November 2013 subject to all participants providing written informed consent from parents and verbal assent from children (Appendix 3.1).

3.2.2 Inclusion/Exclusion criteria

Children with OBPP were the chosen population for this research study. The following inclusion and exclusion criteria were applied. Inclusion criteria were: 1) aged between 6-18 years at time of assessment; 2) participants and parents/guardians willing to give written and informed consent; 3) diagnosis of OBPP Exclusion criteria were: inability to follow simple commands; co-existing diagnosis that influenced upper limb movement; surgery or botulinum toxin intervention within the past 6 months.

3.2.3 Sample size

The required sample size was calculated based on detecting a difference of 60º with a SD 30º in external rotation ROM during a hand-to-head test between children with OBPP and healthy controls. These figures were based on previously published data by Mosqueda et al. (2004) (Table 3.1).

Table 3.1: Amount of shoulder external rotation required to perform tasks "hand to head" and "hand to spine pocket"

*Units of measurement: Degrees; OBPP: Obstetric brachial plexus palsy; TDC: Typically developing chidren; Mean(standard deviation) *Significantly different from normal (p<0.05)*

Adapted from Mosqueda et al. (2004)

	Hand to Head		**Hand to Spine Pocket**	
	OBPP	TDC	OBPP	TDC
External Rotation	76*(29)	-20(20)	-63*(33)	-30(12)

A second measure, based on a mean modified Mallet score for External Rotation in children with Erb's Palsy of 3.2±0.9, was considered but as this data was non-parametric and TDC would be expected to achieve full marks it was not used in sample size calculation (Table 3.2) (Russo et al., 2014).

Table 3.2: Means and standard deviations of the modified Mallet scores for patients with Erb's palsy and extended Erb's palsy

SD – standard deviation

Adapted from Russo et al. (2014)

Position	Erb's Palsy Mean ± SD	Extended Erb's Palsy Mean ± SD
Abduction	3.7 ± SD 0.5	3.0 ± SD 0.0
External Rotation	3.2 ± SD 0.9	3.7 ± SD 0.8
Internal Rotation	3.7 ± SD 0.9	3.0 ± SD 0.8
Hand-to-Mouth	3.8 ± SD0.7	3.8 ± SD 0.0
Hand-to-Neck	3.3 ± SD0.7	2.5 ± SD 0.4
Hand-toSpine	2.5 ± SD 0.5	2.0 ± SD 0.0

A significance level of 0.05 and a β of 0.10 (90% power) was set. Sample size for each group was determined using the calculation described by Pocock (1983) given as; $n = 2s^2$/(‘. ‘˳ · ‶Ω| ȟ). Where σ is the SD, μ is the mean difference expected between the two groups using a two sample t-test, α is the significance level ($P < 0.05$) and β is the power (0.90) and f (α, β) is 10.5. The power calculation was based on a two-tailed test which resulted in a sample size of 10 participants in each group.

3.2.4 Participant recruitment

There were two methods of participant recruitment identified. Firstly, participants within the eligible age range were identified from the CRC physiotherapy database by the primary investigator. For ease of accessibility, only children attending the main centre were included initially. This was to minimise travel distance for participants. Should an insufficient number of participants be obtained from the first database, a second database of children attending a satellite centre was available.

Secondly, the Erb's Palsy Association of Ireland was contacted to inform them of the research project. A cover letter explained the aims and objectives of the research study (Appendix 3.2) and the participant information leaflet was provided for dissemination amongst members (Appendix 3.3). Any interested members were invited to contact the primary investigator for further information.

For the participants on the CRC physiotherapy database, the treating therapist of each eligible participant was contacted to identify participants fitting the exclusion criteria. A list of suitable potential participants was compiled and each was allocated a unique identifying number. Ten participants were selected from this list at random by an independent assessor who had access only to their unique identifying numbers. Once selected, the treating therapist acted as a gatekeeper by approaching both the participant and their guardians first to establish their interest in participating. This method of initial contact was to facilitate ease of refusal. If they expressed interest, the primary investigator contacted them, either by phone or in person at a therapy appointment, to further explain the details of the research. The cover letter (Appendix 3.4) and patient information leaflet were posted or given to all participants (Appendix 3.3). All participants had informed consent forms signed by their guardian as they were under the age of consent (Appendix 3.5). Random numbers were selected from the list until 10 consenting participants were sourced.

Age-matched controls were recruited by open invitation to clinic staff and service users for their children to participate within the study.

Each participant was given a unique identification code stored in a separate database. This was to comply with ethical recommendations that no identifying details were attached to their data.

3.3 Questionnaire

A questionnaire was developed by the primary researcher to obtain information about the participants (Appendix 3.6). This included previous surgical history, difficulty with ADL, if any, and presence of pain or cosmetic concerns. This was reviewed by two senior clinicians who work with children with OBPP, an occupational therapist and physiotherapist. It was also piloted by a parent of a child with OBPP to identify any difficulty with comprehension of questions. The questionnaire was posted to the participants on their agreement to participate in the study along with the patient information leaflet and consent form.

3.4 Instrumentation

The following section outlines the instrumentation and kinematic model used to measure upper limb movements.

3.4.1 Motion capture system

The Gait Laboratory at the CRC is equipped with an optoelectronic tracking system composed of 4 CODA cx1 optical scanners (Charnwood Dynamics Ltd. Leicestershire) (Figure 3.1 and Figure 3.8). This is an active marker system that tracks infra-red light emitting diodes (LED) on bony landmarks. All kinematic calculations were performed using Codamotion ODIN v1.03.01.08 software.

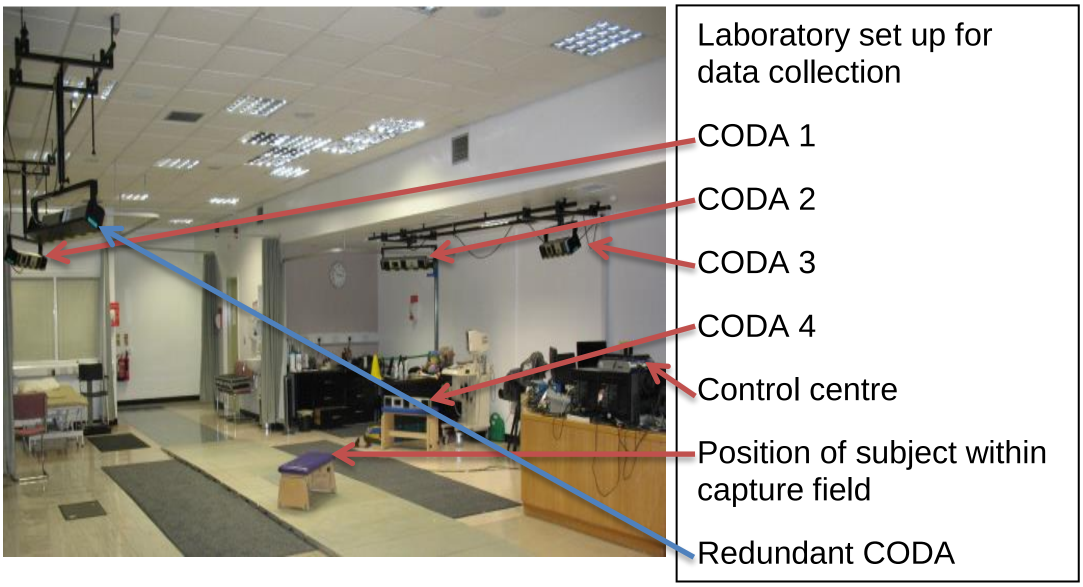
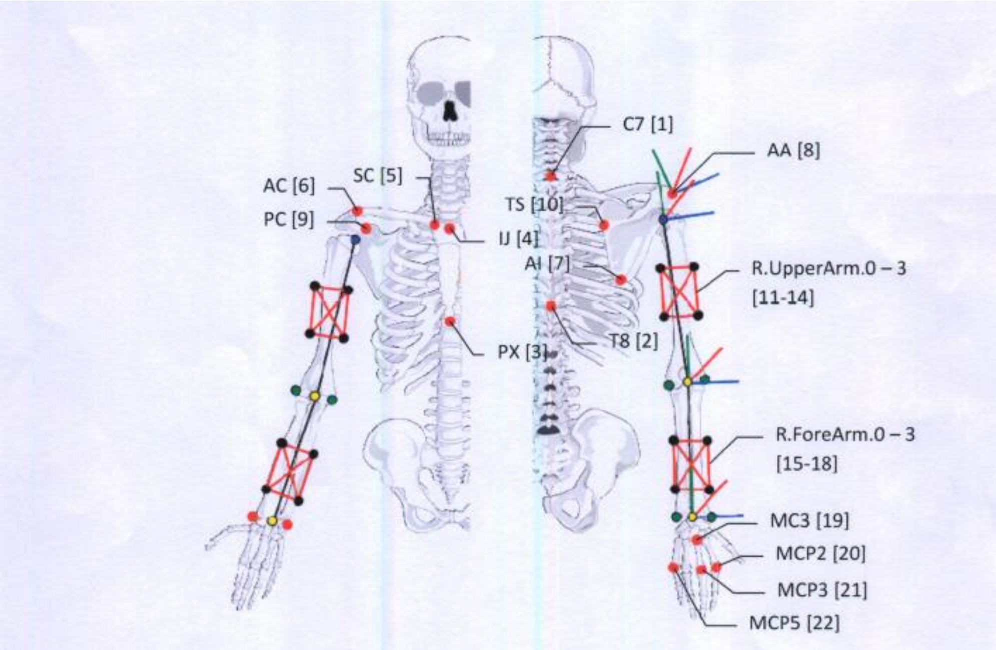


Figure 3.1 Laboratory set up for data collection

3.4.2 Marker placement protocol

To facilitate comparison with previous research and communication of results, the ISB recommendations for upper limb kinematics were implemented (Wu et al., 2005). They specify the anatomical bony landmarks used to define each segment creating a rigid linked segmental model as per Figure 3.2 below and in Table 2.4 in Chapter 2 Development of Methodology.



Adapted from (Wu et al., 2005)

Figure 3.2: Bony landmarks for upper limb model

C7: Spinous process of 7th cervical vertebrae; T8: Spinous process of 8th thoracic vertebrae; PX: Processus xiphoideus; IJ: Incisura jugularis; SC: Sternoclavicular joint; AC: Acromioclavicular joint; TS: Trigonum spinae scapulae; AA: Angulus acromialis; PC: Processus coracoideus; AI: Angulus inferior; GH: Glenohumeral rotation centre; EL: Lateral epicondyle; ML: Medial epicondyle; US: Ulnar styloid; RS: Radial styloid; MC3: Styloid process of metacarpal 3; MCP2: Metacarpophalangeal 2; MCP3: Metacarpophalangeal 3; MCP5: Metacarpophalangeal 5

While the ISB defined what anatomical landmarks to track, they did not recommend how to track them. In this research study the thorax, hand, sternoclavicular joint and scapular landmarks were defined by active LED skin surface markers.

Following a comprehensive literature review of measurement methods, described in Chapter 2 Development of Methodology, the AM of tracking scapular movement was chosen as the most suitable method to track dynamic scapular movement for the purposes of this study. As discussed in Chapter 2 Development of Methodology: Section 2.4.2.2.4.3 calibration of the upper limb model was essential to increase accuracy. Based on two observations, the potential inability of participants with OBPP to achieve 90º abduction and the conclusion by Duff et al. (2007) that most activities of daily living were achieved below 100º humeral elevation, a single static calibration was used in this research. Through a static acquisition using a dynamic pointer, the relative positions of the scapular anatomical reference LED were referenced to the technical coordinate frame of the AC with the arm at rest, elbow flexed and forearm pronated with palm resting on ipsilateral knee was considered repeatable and valid for the purpose of this research (Figure 3.3). Movement of the scapula was then determined based on movement of the cluster, and not on the skin markers which are prone to skin movement artefact during dynamic activity as discussed in Chapter 2 Development of Methodology: Section 2.4.2.2.4.1.

Humeral lateral and medial epicondyle and radial and ulnar styloid were digitised by the dynamic pointer and related to the technical frames of the upper and forearm clusters. These virtual points were then used in segment anatomical frame definitions. The acromioclavicular joint was defined as the base of the cluster. The GH joint centre was calculated by a linear regression method as recommended by ISB (Wu et al., 2005).

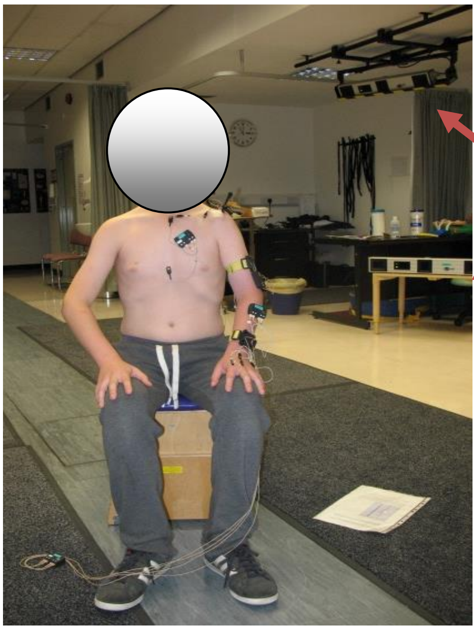


Figure 3.3: Calibration position

3.4.3 Joint and segment kinematics

Both joint and segment kinematics were described in this research. Joint kinematics describe relative attitude of two adjacent bony segments e.g. GH joint. Segment kinematics describe the relative attitude of one bony segment with respect to the GCS or a non-adjacent bony segment e.g. thorax with respect to humerus. As recommended by the ISB, each joint coordinate system relates back to the proximal segment's coordinate system.

The upper limb model defined one segment the thorax and six joints: sternoclavicular; acromioclavicular; TH; GH; ST; elbow and wrist joints. Describing kinematics of all joints was not possible in this research. Therefore, as the most commonly affected joints in OBPP, the TH, GH, ST, and elbow joints were explored in this study. Each has six degrees of freedom about three rotation axes, with the exception of movement about the Xf-axis (Table 3.3) in the elbow joint, known clinically as the carrying angle. This was a passive response to elbow F/E and was not reported.

The GCS relative to the laboratory is "XYZ" where the "X" axis points anteriorly, "Y" axis points medially and the Z" axis points superiorly. With respect to this GCS, the LCS of the thorax according to the ISB is “XYZ” where the “X” axis is the same but “Y” and “Z” axes are reversed.

Table 3.3: Description of the local coordinate systems used in this study for each joint examined

LCS: Local coordinate system; ISB: International society of biomechanics; IJ: Incisura jugularis; AA: Angulus acromialis; GH: Glenohumeral; US: Ulnar styloid; PX: Processus xiphoideus; T8: Thoracic spinous process 8; C7: Cervical spinous process 7; AI: Angulus inferior; TS: Trigoneum spinae; EL: Epicondyle lateral; EM: Epicondyle medial; RS: Radial styloid

Adapted from (Wu et al., 2005)

LCS (ISB)	Origin of LCS	Axis of Local Coordinate System
Thorax	IJ	X_t: common line perpendicular to the Zt- and Yt-axis, pointing forward Y_t: line connecting the midpoint between PX and T8 and midpoint of IJ and C7, pointing upward Zt: line perpendicular to plane formed by IJ and C7 and midpoint between PX and T8, pointing right
Scapula	AA	X_s: line perpendicular to plane formed by AI, AA, TS, pointing forward Y_s: common line perpendicular to Xs- and Zs-axis, pointing upward Z_s: line connecting TS and AA, pointing to AA
Humerus	GH	X_{h2}: common line perpendicular to the Zh2- and Yh2-axis, pointing forward Y_{h2}: line perpendicular to the plane formed by Yh2 and Yf, pointing to the right. Z_{h2}: line perpendicular to the plane formed by Yh2 and Yf pointing to right
Forearm	US	X_f: line perpendicular to the plane through US and RS and the midpoint between EL and EM, pointing forward Y_f: line connecting US and the midpoint between EL and EM, pointing proximally Z_f: common line perpendicular to the Xf and Yf-axis, pointing to the right

3.4.3.1 Definition of joint and segment rotation

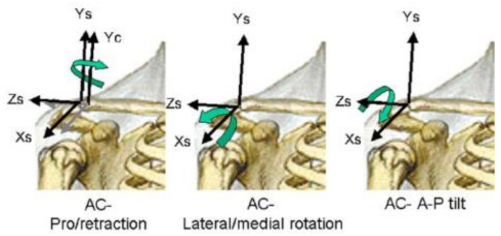
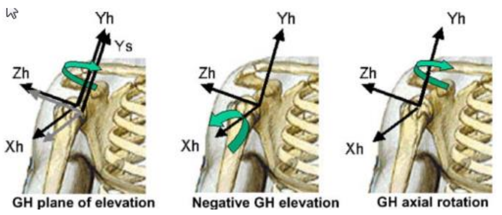
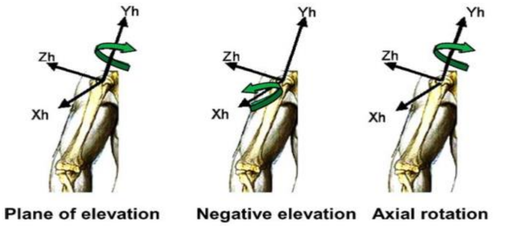
Joint and segment rotation permits definition of angles achieved by each joint through space. Their calculation, for the purpose of this research, is described in this section.

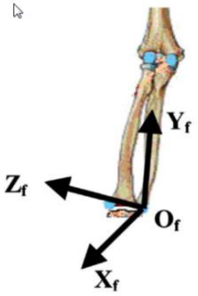
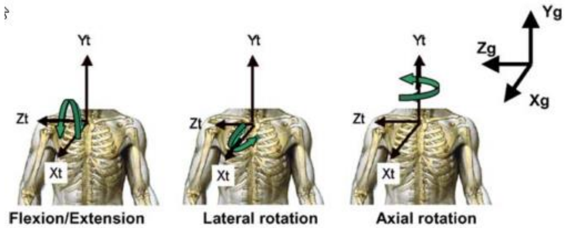
As recommended by the ISB, rotations were described using Euler angles (Table 3.4). Rotations of the coordinate system should be described with the distal coordinate system in relation to the proximal coordinate system. To allow for clearer interpretation of these angles, coordinate systems of the proximal and distal body segments were aligned to each other by introduction of anatomical orientations. ISB recommended specific sequences as these most closely resemble clinical definitions of joint and segment motions. The sequences of rotation were as follows: 1st rotation around one of the common axes; 2nd rotation around the (rotated) axis of moving coordinate system and 3rd rotation again around one of the rotated axis of moving coordinate system (Wu et al., 2005).

Table 3.4: Description of the Euler sequences used in this study as recommended by the International Society of Biomechanics

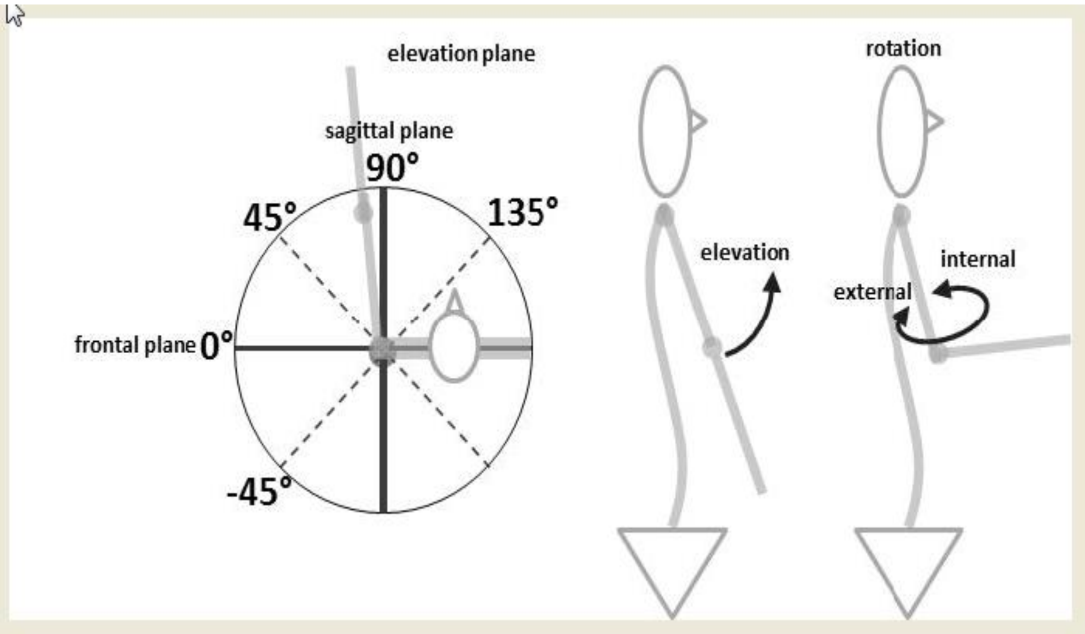
e: Euler rotation; t:Thorax; s: scapula; h: Humerus; f: Forearm; -ve: Negative; +ve: Positive; GH: Glenohumeral; TH: Thoracohumeral; GCS: Global coordinate system

Adapted from (Wu et al., 2005)

Joint	Euler Sequence	Name of rotation
Scapula/thorax: ST Joint  	e1: Yt e2: X e3: Zs	Retraction (-ve); Protraction (+ve) Lateral (upward) (-ve); Medial(downward)(+ve) Anterior (-ve); Posterior tilt (+ve)
Humerus/scapula: GH Joint  	e1: Y e2: X e3: Y''	Plane of elevation: 0¯is abduction; 90¯is forward flexion GH elevation (-ve) Axial rotation: External (-ve); Internal (+ve)
Humerus/thorax: TH Joint  	e1: Yt e2: Xh e3: Yh	Plane of elevation: 0¯is abduction; 90¯is forward flexion Elevation (-ve) Axial rotation: External (-ve); Internal (+ve)

Joint	Euler Sequence	Name of rotation
Forearm/Humerus: Elbow Joint 	e1: Zh e2: Xf e3: Yf	Extension (-ve); Flexion (+ve) *Carrying angle (not reported)* Supination (-ve); Pronation (+ve)
Thorax/GCS 	e1: Z e2: X e3: Y	Flexion (-ve); Extension (+ve) Axial rotation: Right (-ve); Left (+ve); Lateral flexion: Right (+ve); Left (-ve)

TH and GH angles were defined according to the Globe system described by Doorenbosch et al. (2003) and Pearl et al., (1992) in which orientation of the arm was described in the order of “plane of elevation” (y), “elevation” (z) and “axial rotation” (y). In this definition, 0¯POE represents the frontal plane, 90¯POE is equal to the sagittal plane (Figure 3.4).



(Doorenbosch et al., 2003)

Figure 3.4: Globe system of angle definition

3.5 Tasks analysed

The Mallet scale is the most widely used assessment scale of functional tasks in children with OBPP and has been used in previous studies assessing 3D upper limb kinematics of children with OBPP (Russo et al., 2014, Nicholson et al., 2014). It forms part of the assessment for all children with OBPP who attend the CRC and therefore it was considered to be the most appropriate functional measure to use in this research study.

The original Mallet scale has been modified to include assessment of Internal Rotation Task since this movement was affected after surgical intervention to address external rotation contractures (Abzug et al., 2010). The subject actively performs six different shoulder movements:

Abduction, External and Internal Rotation, Hand-to-Mouth, Hand-to-Neck and Hand-to-Spine. Each shoulder movement is subsequently graded on a scale of 1 (no movement) to 5 (normal motion similar to unaffected side) with a possible maximum score of 30 (Figures 3.5 and 3.6).

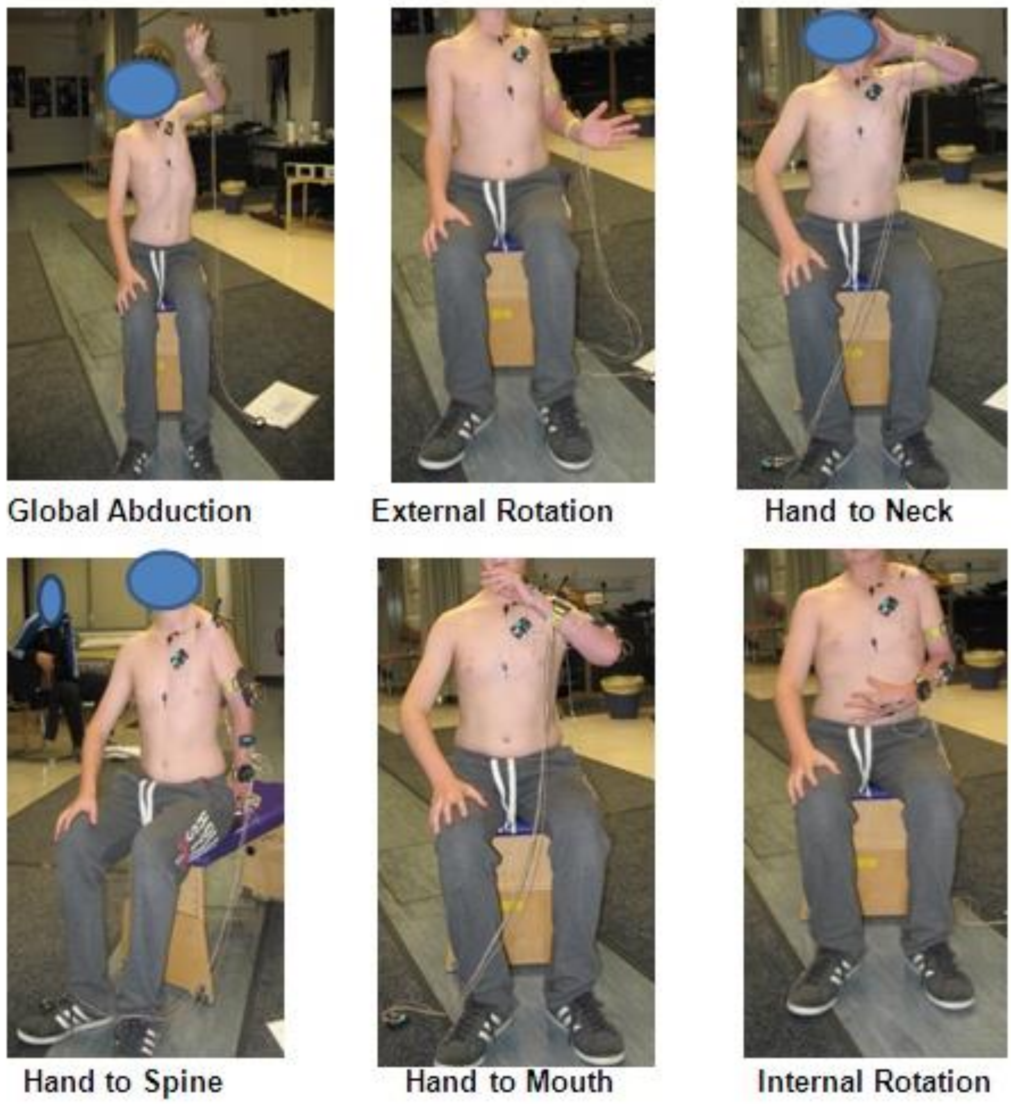


Figure 3.5: Tasks performed by child with obstetric brachial plexus palsy

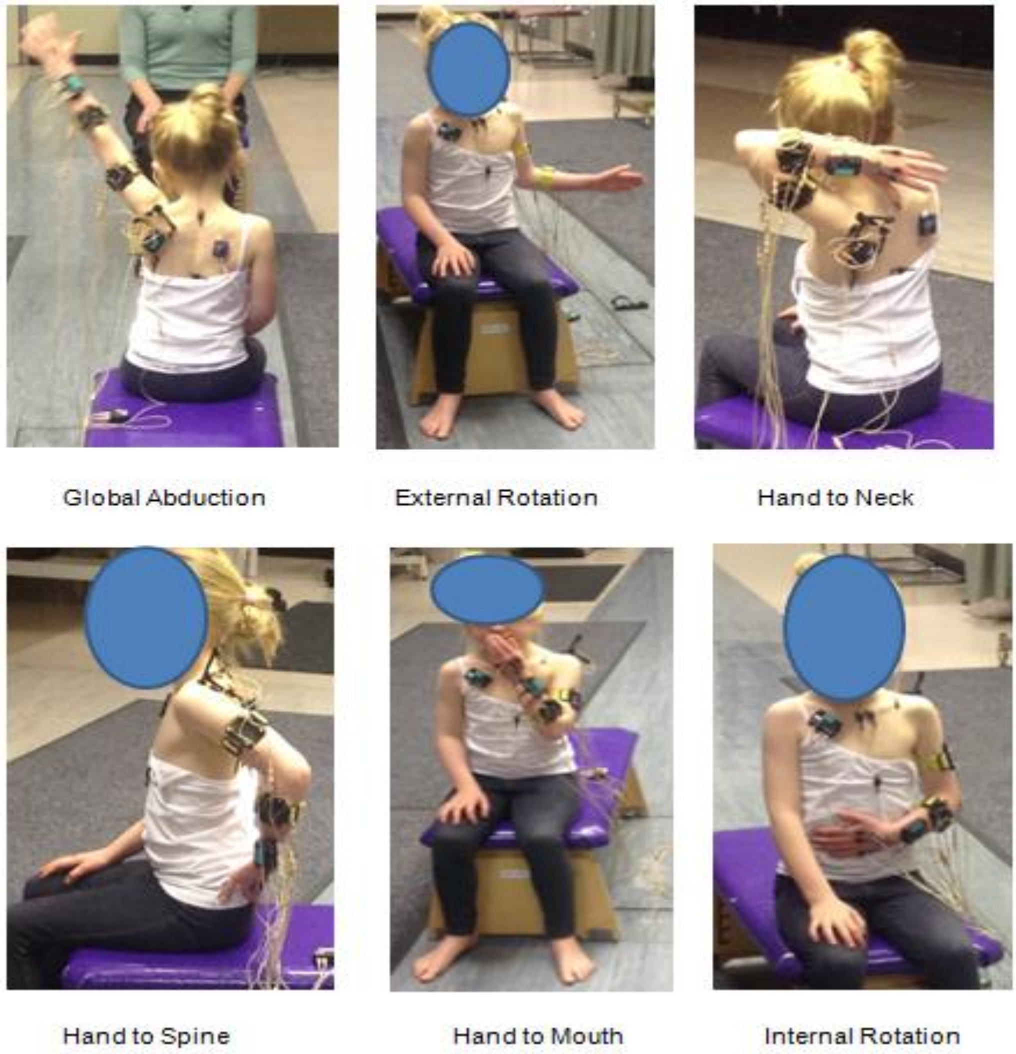


Figure 3.6: Tasks performed by a typically developing child

3.6 Testing protocol

This section describes the testing protocol as implemented for each participant in this study. Children with OBPP attended for initial assessment wearing a halter neck or string top if female and bare chested if male. Each participant was seated within the capture area with an alignment that optimised marker visibility as much as possible for all tasks (Figure 3.7).

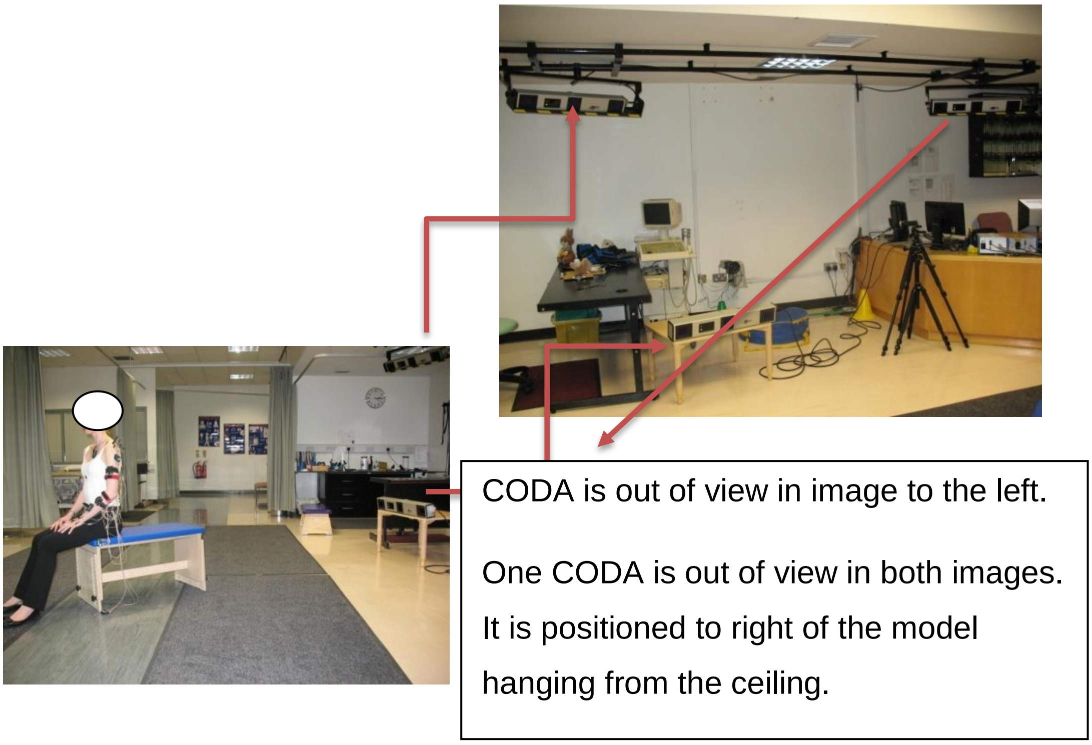


Figure 3.7: Position of subject within capture field

The four CODAs formed a semi-circular capture field with one CODA positioned high in front and to the side of the participant to capture the anterior makers and one positioned lower down behind and to the side of the participant to facilitate view of forearm markers in the Hand-to-Spine Task as per Figures 3.7 and 3.8. This was the best set-up possible with a four camera system.

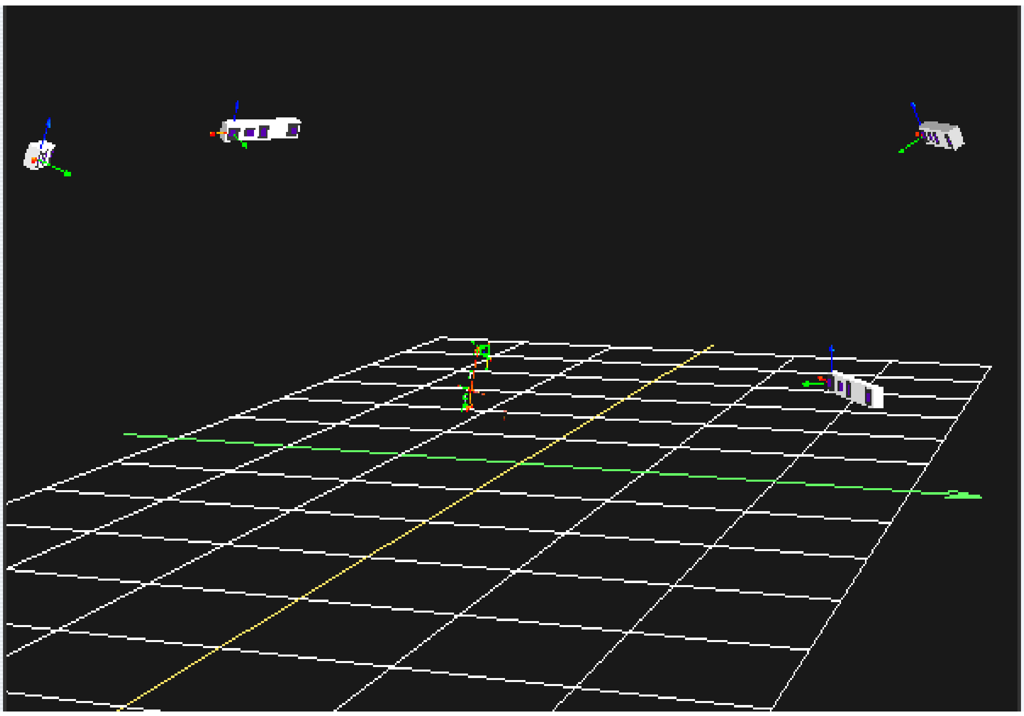


Figure 3.8: CODA camera set up for right hand analysis

The participant sat at the end of the bench, back unsupported to allow for compensatory movements of the thorax, with hips and knees at 90¯, feet flat on the floor, affected arm relaxed and hand resting palm down, where physically possible, on ipsilateral thigh (Figure 3.9).

Figure 3.9: Start position for all tasks

Markers were placed on each of the bony landmarks. As a quality check, a colleague, experienced in the application of the marker placement protocol, verified accurate marker placement. Virtual landmarks and a static calibration trial were captured using pointer acquisition. The stick figure representation was visually checked for accuracy after calibration (Figure 3.10).

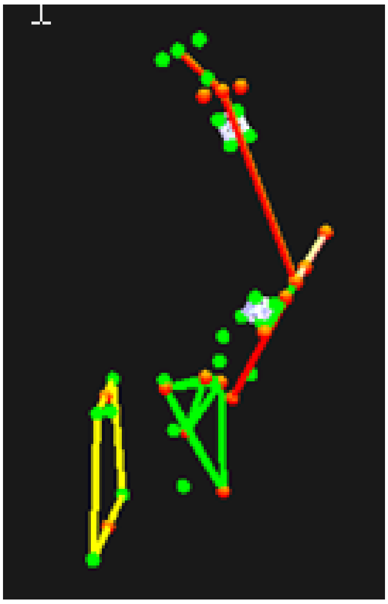


Figure 3.10: Stick figure as produced by ODIN for point of task achievement in the Abduction Task

During task performance the primary investigator sat directly in front of the participant. Each task was verbally explained using standard instructions and demonstrated to the participant. Instructions given for each task were:

¶ Hand to Mouth Task: “Bring the tips of your fingers to your mouth”

¶ Abduction Task: “Point thumb to the ceiling and bring your arm out to the side and over your head”

¶ Hand to Neck Task: “Bring palm of your hand to the back of your neck”

¶ External Rotation Task: “Keep your elbow in by your side and bring hand out to the side”

¶ Internal Rotation Task: “Keep your elbow by your side and bring palm of your hand into your tummy”

¶ Hand to Spine Task: “Bring thumb to your lower back”.

Participants were permitted a minimum of one practise trial with maximum of three to ensure understanding of the task and minimise fatigue. Three trials of each task were then recorded.

For each trial, the stick figure and marker visibility summary were checked by a colleague, an experienced clinical engineer, who acquired the data. If insufficient marker view was recorded, tasks were repeated until maximum view was obtained. Certain tasks obstructed marker view mainly the anterior thoracic markers during the Hand-to-Mouth Task (28% OBPP; 46% TDC) and in some participants during the Abduction Task (42% OBPP; 10% TDC), forearm and hand markers in the Hand-to-Spine Task (42% OBPP; 40% TDC). This was due to orientation of the upper limb and compensation patterns of participants with OBPP.

Each participant with OBPP returned to the laboratory for repeat testing no sooner than 48 hours and within two weeks of their initial assessment to complete the test-retest reliability aspect of the study.

TDC attended for one assessment session following the above protocol. The affected arm was the non-dominant arm of participants with OBPP.

Based on this fact and its use in previous studies (Jaspers et al., 2011c) the non-dominant arm of TDC was tested.

3.7 Data collection sessions

Informed written consent was obtained from guardians and verbal assent obtained children prior to data collection. A complete examination took approximately 35-45 minutes. This involved a brief explanation of the theory behind the upper limb model, the purpose of the research study, participant set up, task demonstration and finally, data collection of three trials of task performance. The second session of data collection for the reliability study was shorter as the participant was familiar with the procedure. Each participant with OBPP completed the questionnaire with their parents prior to attending the first testing session.

3.8 Data processing

Data were saved and backed up to a secure server, then inspected and prepared for statistical analysis. Raw kinematic data were filtered using and un-weighted moving average filter with a filter width of +/- 4 samples. All data were filtered using Codamotion ODIN software (v1.06 Build 01 09). The following section describes this process and the rules used for data reduction or exclusion.

3.8.1 Definition of task start and end points

The start and end points of the task were defined by the metacarpal 3 marker for all movements in TDC as this was consistently the first part of the arm to move from its resting posture. This was defined by visual inspection of both the graphical trajectory of the MC3 marker and observation of the stick figure. For the five tasks, Hand-to-Mouth, Hand-to-Neck, Hand-to-Spine, External Rotation and Internal Rotation, the start of the movement was defined when the hand moved from the resting posture. Abduction Task start point was defined as the initiation of MC3 away from the side of the body. The end was visually identified as the PTA as defined by the modified Mallet scale.

In some participants with OBPP, deviations from these definitions of start and end point were required due to their less defined movement patterns and compensatory strategies. For example, some participants with OBPP initiated movement for some tasks with their elbow joint, therefore this was used to define the start point.

Each trial was visually assessed to ensure sufficient marker view for useable data. ODIN software has a function of “marker visibility summary” which refers to the total period of data capture. In all cases this was longer than the actual movement analysed. For this reason a cut-off in view percentage was not utilised but visual inspection of the timing of marker occlusion, stick figure and ODIN graph output were used to determine whether data were valid.

3.8.2 Technical problems addressed in data processing

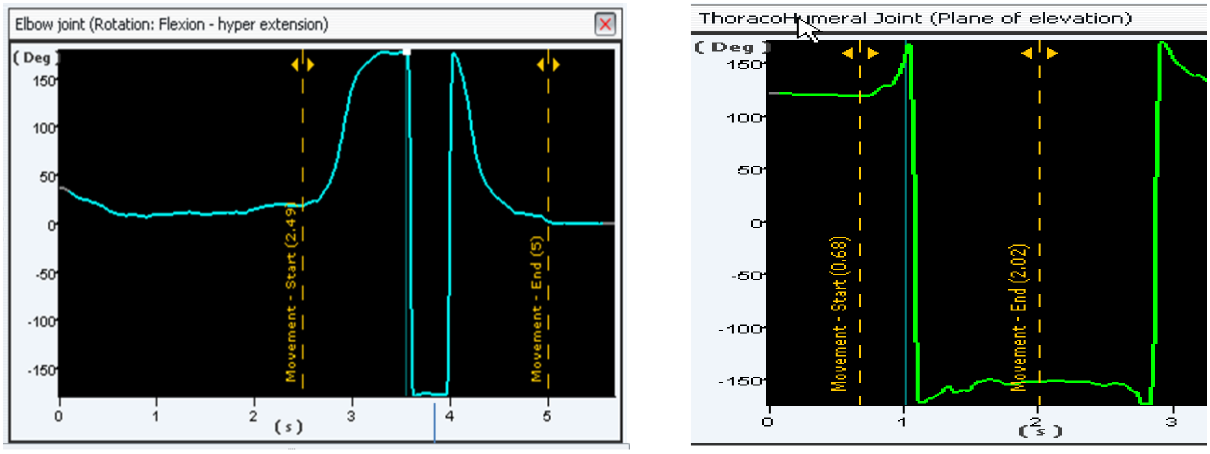
Data defined by start and end points were exported to Microsoft Excel (2010) via MATLAB, using a purpose written function and time normalised for each task, for further inspection and exploration. Joint movements in each rotation axis (Table 3.5) were plotted on a line graph for visual inspection. Calculation of maximum, minimum and range allowed identification of both gimbal lock and spikes in each individual trial. These data were graphed in Excel, amended or discarded based on the commonly-encountered problems, the description of which and rules applied are outlined in Appendix 3.7. These were based on previous research by Jaspers et al. (2011c) and verified by the laboratory clinical engineer. The main problems encountered are briefly described below.

Table 3.5: Joints and rotation axes analysed

Task	Joint	Plane
Abduction	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
External Rotation	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
Internal Rotation	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
Hand-to-Mouth	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
	Elbow	X,Z
Hand-to-Spine	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
	Elbow	X,Z
Hand-to-Neck	Glenohumeral	X,Y,Z
	Thoracohumeral	X,Y,Z
	Scapulothoracic	X,Y,Z
	Elbow	X,Z

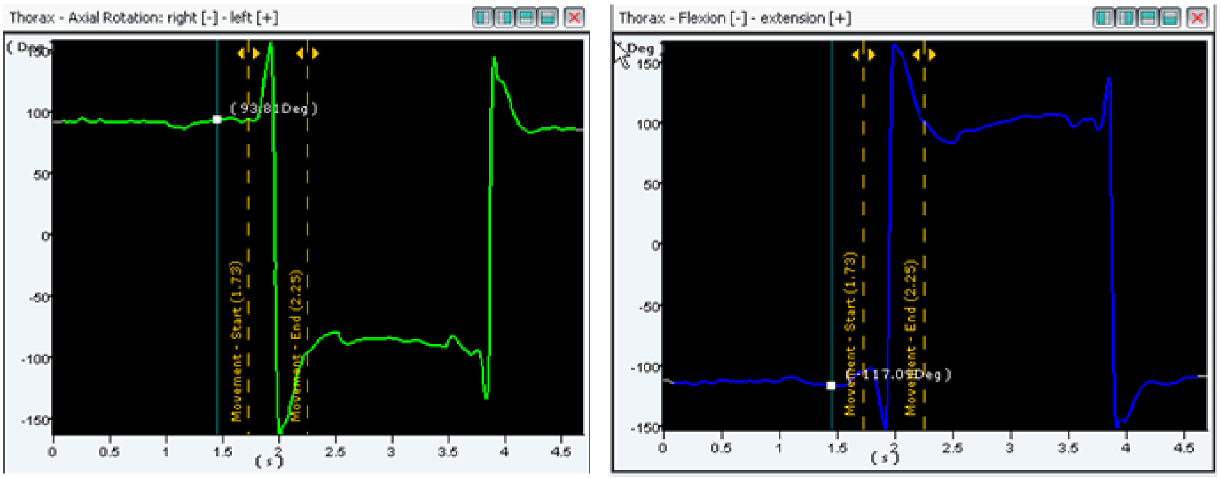
3.8.2.1 Gimbal lock

Graphical output for each task, joint and rotation axis was inspected for the well-recognised problem of gimbal lock (de Groot et al., 1997; Anglin and Wyss 2000; Senk and Cheze 2006). As an angle approaches 180º the graph flips to its negative equivalent within a few frames of movement followed by a reversal a few frames later (Figure 3.11). TDC were most affected as they were capable of achieving the two positions associated with gimbal lock i.e. maximum range of upper limb elevation (180º) and close to 0º with “arm by side”. It was mainly seen in the Abduction, Hand-to-Neck and Hand-to-Spine Tasks and was adjusted for, according to the rules outlined in Appendix 3.7. The start and end of gimbal lock was visually identified and data were either adjusted with +/- 180º or +/- 360º depending on the degree of the flip. There were problems with thorax movement with gimbal lock occurring in 60% of trials of TDC and 30% of children with OBPP. This was due to the position of the participant within the GCS where minimal thorax movement resulted in crosstalk of axes producing gimbal lock. Therefore, it was decided not to interpret these data.



A

B



C

Figure 3.11: Examples of gimbal lock - A) elbow joint during Hand-to-Neck Task; B) thoracohumeral joint plane of elevation during External Rotation Task C) thorax during Hand-to-Mouth Task

3.8.2.2 Spikes of movement

On occasion, marker visibility was unavoidably occluded due to marker orientation, reduced arm mobility in some participants and occlusion by wires. An inherent problem exists with CODA whereby, as the markers move through space they move in/out of view of individual CODAs. This slight shift can result in spikes of movement that are not true. Across large ROM this is not a problem but within small ROM this results in relatively large spikes of inaccurate movement. These two problems contributed to spikes within the graphs that distorted the data (Figure 3.12).

All spikes were identified in Excel output followed by inspection of the 3D stick figure to determine if movement was true. If true movement was verified the data was retained. If the spikes were due to marker view issues, marker reflection, jumping of marker pick-up between CODAs they were deleted. The start and end of the spike were identified based on ODIN output, Excel graph output and timing of stick figure movement. A linear interpolation was applied if the gap was deemed small enough not to impact on the average trace. Otherwise, the trial was discarded.

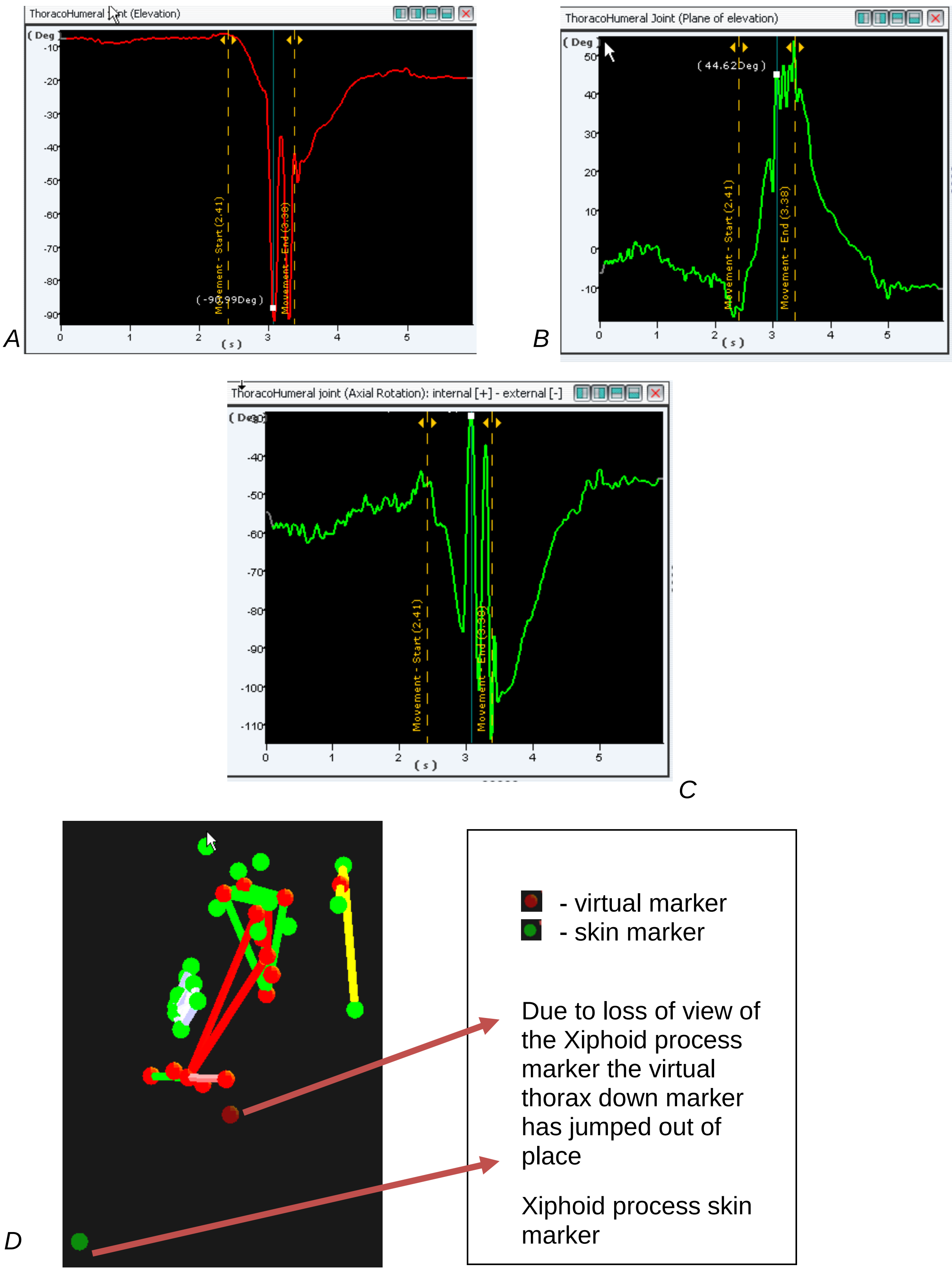


Figure 3.12: Movement spikes due to insufficient marker view

A/B/C: Graphical output of thoracohumeral elevation, plane of elevation and axial rotation; D: Image of stick figure of Hand-to-Mouth Task at point of marker occlusion

3.8.2.3 Erroneous reversal of movement direction

Other problems identified during visual inspection were addressed where possible, or discarded, if not. These included a reversal of graph direction across the Z axis despite the stick figure continuing to move in the same direction (Figure 3.13). This was considered to be a consequence of the arm beside the thorax which can result in illogical angles being determined by the mathematical model (Phadke et al., 2011). This mainly occurred in TDC during the External Rotation Task as participants approached midline from the resting position of hand on knee. In some participants, depending on how they moved, it occurred in the Hand-to-Spine Task. When clearly identified the incorrect direction was addressed by multiplying by -1, otherwise the trial was discarded.

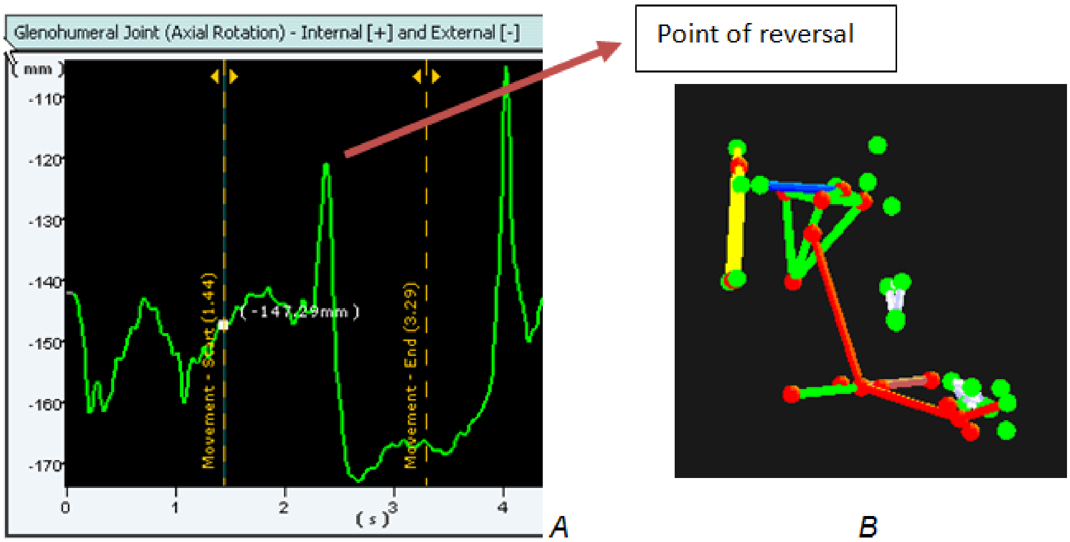


Figure 3.13: External Rotation Task with movement reversal in graph despite stick figure continuing in the same direction

A: Glenohumeral joint axial rotation graph; dashed yellow lines indicate start and end of movement; B: stick figure image at point of movement reversal, it continues to move in the same direction despite the graph reversing its direction

3.8.2.4 Marker Occlusion

Due to the nature of the movements and upper limb orientation, markers were on occasion unavoidably occluded from the CODAs. For example, during the Hand-to-Mouth Task, the marker located on the thorax at IJ could become occluded as the hand approached the mouth (Figure 3.12). In these instances, the size of the data gap was visually analysed in the ODIN software. A linear interpolation was applied if the gap was deemed small enough not to impact on the average trace. If the gap was sufficiently large, the trial was discarded from the average trace.

3.8.3 Data collation once technical problems addressed

Once individual data sets were explored and useable data identified, the average traces of identified joints and rotation axes for each task were graphed for further exploration and analyses. Each trial was plotted both individually and within the group to identify trends of movement and any outliers that skewed data. All outliers were retained unless their presence was explained by technical issues. All trials included in the final analysis of both children with OBPP and TDC are outlined in Appendices 3.8 and 3.9. The final data were then plotted to produce graphical representations of the dynamic performance of each task and prepared for statistical analysis to address the two individual aims of this research study.

3.8.4 Variables for analysis

Chosen variables to be analysed were based on clinical utility and previous studies identified in the literature. The variables extracted were: ROM (degrees - maximum minus minimum); PTA (degrees-end point) and duration of movement (time - seconds). ROM during performance of functional tasks in children with OBPP has not been analysed in the literature therefore it was a novel aspect of this research. PTA allowed comparison with previous research.

3.9 Statistical analysis

All variables were examined for normal distribution with the Shapiro Wilk test using the statistical programme IBM SPSS Statistics Version 22 (Appendix 3.10).

3.9.1 Reliability

Reliability reflects the amount of error both random and systematic inherent in any measure. It is important to remember that the reliability of a measure is intimately linked with the population to which one applies the measure. It is an interaction of the instrument, the specific group of people, the administrator of the test and the situation (Streiner and Norman, 2008).

To examine test-retest reliability the ICC and their 95% CI were calculated for task duration, ROM and joint angles at PTA using a one way random effects model, $ICC_{(2,K)}$ (Rankin and Stokes, 1998). The ICC is a measure of the reliability of measurements or ratings. It describes how strongly units in the same group resemble each other and reflects the extent to which a measurement instrument can differentiate between individuals. The single measure was used as it is an index for the reliability of ratings of a single rater. K refers to the fact that the mean of three trials was used, not a single trial. The ICC cut-off point is arbitrary and should be decided based on the purpose of the instrument (Kottner et al., 2011). A reliability coefficient of ≥0.75 has been suggested as being a minimal requirement for a useful instrument (Streiner & Norman, 2008). Therefore, this standard was chosen for the purpose of this study.

As the ICC is dimensionless, its interpretation in terms of an individual score is difficult. Consequently, reporting the SEM is useful as it is expressed in the same units as the original scores (McGinley et al., 2009). The SEM was calculated with the formula $SD*\sqrt{(1-ICC)}$. The SEM is an absolute measure of reliability. It determines the amount of variation or spread in the measurement errors for a test. A measurement error is the difference between an examinee's actual or obtained score and the theoretical true score counterpart. MDC was reported for each variable as a measure of the clinical relevance of the difference (de Vet et al., 2006). It was calculated using the formula 1.96*√2*SEM.

As a high correlation coefficient does not automatically imply good agreement between measures, further analysis was conducted using Bland and Altman (B&A) plots to compare the variables at the two time points (Bland and Altman, 1986). B&A plots examine the agreement between two quantitative measures. They quantify agreement by constructing limits of agreement (LOA). These statistical limits are calculated by using the mean and SD of the difference between two measurements. The graph produced in GraphPad Prism® is a scatter plot XY in which the Y axis shows the difference between the paired two measurements (B-A) and the X axis presents the average of these two measures (B+A/2). It was recommended by Bland and Altman (1986) that 95% of data points should lie within the ±2SD of mean difference. This allowed investigation of the existence of any systematic difference between the time points (i.e., fixed bias) and to identify possible outliers.

3.9.2 Kinematic differences between TDC and OBPP

Angular waveforms of both TDC and children with OBPP were graphed using Microsoft Excel (2010). For each task a typical waveform of each joint and rotation axis was calculated for TDC using mean +/- 1SD. Each individual average trace of three trials for children with OBPP was then plotted over this typical band. These graphs were visually analysed for typical movement patterns and compensatory strategies. Either the independent student t-test (parametric data) or the Mann-Whitney U test (non-parametric data) was used to identify significant differences between TDC and children for both variables: PTA and ROM.

Reliability results are presented in Chapter 4. Kinematic results are presented in Chapter 5. Each set of results are followed by a brief discussion in the context of current literature. Finally, conclusions and implications for clinical practice and future research are presented in Chapter 6.

Chapter 4 Reliability Study: Results and Discussion

4.1 Introduction

This chapter outlines the results of the reliability study. Firstly, participants' demographic data are outlined. Secondly, test-retest reliability in children with OBPP of a 3D-ULMA model, using the AM of scapular tracking, in analysing kinematic patterns of functional task performance is presented. This is followed by a discussion of these results within the context of current literature. The model was found to have inconsistent inter-session reliability in this population. No task, rotation axis or joint achieved total acceptable reliability. Nonetheless, the Abduction Task and elevation plane were considered to be acceptably reliable for clinical application.

4.2 Sample population

4.2.1 Normative sample population

Ten TDC were recruited from work colleagues. The average age was 9 years 9 months (SD 2.6 years), range 6-15 years. All TDC were right hand dominant. As the affected hand tested in children with OBPP was non-dominant, the TDC's left hand was tested. Each TDC attended for one assessment session only.

4.2.2 Participants with OBPP

All eleven children with OBPP were recruited from the CRC databases. Informed written consent was obtained from guardians. Verbal consent was obtained from each child. The average age was 10 years (SD 2.5 years), range 7-15 years. There were representatives from NC grades I-III.

One complete data set for participant 11 had to be discarded due to a technical issue. This excluded the participant from the reliability study. The second data set was used in the cross-sectional study to describe characteristic differences between movement patterns of children with OBPP and TDC.

4.2.2.1 Details of participants with OBPP

Of participants with OBPP 8 had a birth weight of >4kg with 2 <4kg. One participant had no record of birth weight. Six presented with shoulder dystocia at birth. Five participants had a non-instrumented delivery, five had vacuum and one forceps assisted delivery. Six had their left and five their right limb affected. Demographic data of participants with OBPP and TDC are presented in Table 4.1 with specific details of children with OBPP in Table 4.2.

Four children with OBPP NC II had microsurgery due to clinically assessed incomplete spontaneous recovery. Three of these four participants proceeded to secondary musculoskeletal surgery to augment functional ability. These included subscapularis release in isolation and in combination with latissimus dorsi transfer; transfer of flexor digitorum superficialis to extensor carpi ulnaris and radius. Two participants, who did not have microsurgery, had secondary musculoskeletal surgeries. One was a child, NC I, who wanted to improve passive external rotation to participate in martial arts. The second was a younger child, NC III, who underwent early musculoskeletal surgery rather than microsurgery after seeking a second opinion on management.

Table 4.1: Participant demographic data

	OBPP (n=11)	TDC (n=10)
Age Mean (Standard Deviation)	10 years (2.5)	9 years 9 months (2.6)
Gender		
¶ Male	7	6
¶ Female	4	4
Hand Preference		
¶ Right	5	10
¶ Left	6	0

Table 4.2: Demographic data specific to participants with obstetric brachial plexus palsy

	OBPP
Laterality	
¶ Right	6
¶ Left	5
Narakas' Classification	
¶ Grade I	2
¶ Grade II	7
¶ Grade III	2
¶ Grade IV	0
Birth Weight	
¶ >4500g	8
¶ <4500g	2
¶ Unknown	1
Shoulder Dystocia	
¶ Present	7
¶ Absent	3
¶ Unknown	1
Microsurgery	
¶ Nerve Graft (C5,6,7)	3
¶ Nerve Transfer (unknown)	1
Muscle Release	
¶ Subscapularis Release	4
Muscle Transfer	
¶ Latissimus dorsi	1
¶ Latissimus Dorsi and Teres major	1
¶ Flexor Digitorum superficialis to wrist extensors	1
Bone Surgery	0

Distribution of surgical intervention with respect to NC is outlined in Table 4.3.

Table 4.3: Surgical intervention as per Narakas' Classification

Participants (number)	Microsurgery	Nerve Transfer	Muscle Release	Muscle Transfer	Bony Surgery
Group I (2)	-	-	1	-	-
Group II (7)	3	1	2	2	-
Group III (2)	-	-	1	1	-

4.3 Questionnaire

Ten of the eleven participants with OBPP returned the specifically designed questionnaire. Results are presented in Table 4.4.

Table 4.4: Results of questionnaire

	Yes	*No*
Assistance with Activities of Daily Living	*7*	*3*
¶ *Hair*	*4*	*6*
¶ *Laces*	*5*	*5*
¶ *High Reaching*	*5*	*5*
¶ *Dressing*	*2*	*8*
¶ *School*	*1*	*9*
¶ *Other*	*1*	*9*
Pain	*3*	*7*
Sensation		
¶ *Difficulty feeling objects*	*3*	*7*
¶ *Pins and Needles*	*3*	*7*
Satisfied with ability	*7*	*3*
Cosmetic concerns	*2*	*8*

Both participants with NC grade III reported difficulty with ADL. One of these participants reported difficulty with high reaching only, while her guardian reported dissatisfaction with functional ability. The other participant of NC III had difficulty across all functional levels. Five participants with NC grade II reported a need for varying levels of assistance. The girls consistently reported difficulty with hair, while laces and high reaching caused problems for both genders and all NC grades. One higher functioning participant of NC grade I reported difficulty with sporting activities. The participant who reported difficulty in school was NC grade II, attending secondary school and required assistance with practical subjects e.g. chemistry.

Of the three who reported pain, pins and needles were also present. Two identified their shoulder as the source of pain especially when stretching while one older girl identified thumb pain during specific activities.

In the comments section, frustration, difficulty with sport and school yard games and a desire to improve active ROM were expressed. Only two participants mentioned cosmetic concerns with function being the main priority of both child and parent.

4.4 Reliability of kinematic parameters

The following section describes the results of the test-retest reliability of a 3D-ULMA model, using the AM of scapular tracking, in analysing upper limb kinematics in children with OBPP.

Overall, the Abduction Task had the highest ICC and lowest SEM values across each joint and rotation axis. The other tasks were not consistently reliable for each joint or rotation axis. Not one joint achieved acceptable levels of reliability across all rotation axes. With specific reference to the ST joint all SEM values were found to be <9º. The Hand-to-Neck Task had the largest SEM values while the Internal Rotation Task had the lowest. SEM values for TH and GH AR at PTA were consistently high across all tasks. Outliers were seen in each task however, as no one participant was consistently responsible, they were not excluded from analysis.

4.4.1 Statistical measures used to evaluate reliability

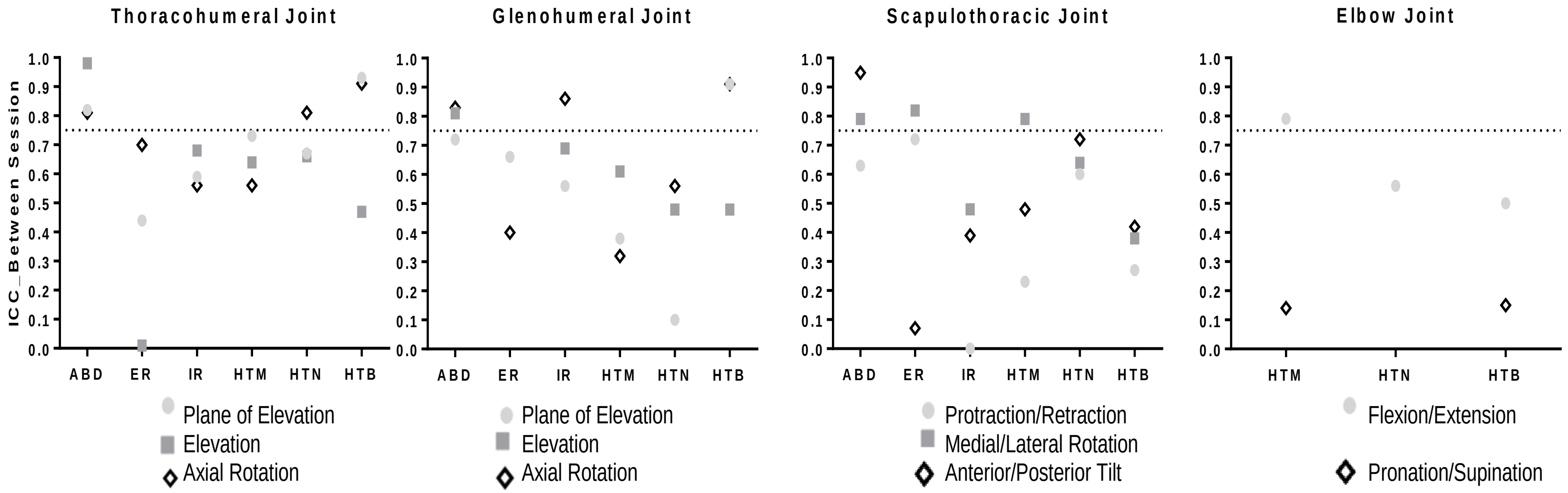
As no one statistical test can capture accurate reliability of a measure, several methods are presented to provide a more comprehensive analysis (McGinley et al., 2009).

B&A plots (Bland and Altman, 1986) evaluate the agreement between two measures. In exploratory data analysis they were applied to the variables, ROM and PTA. This allowed clear visualisation of outliers, systematic difference or fixed bias and the 95% LOA between the two time points.

ICCs are also presented for each variable to examine agreement between the two time points.

In isolation, correlation indices do not tell us whether the measures are “reliable enough” and high values can potentially hide measurement errors of clinical importance (McGinley et al., 2009). Therefore SEM, an absolute measure that expresses variability within the units of the measurement method (degrees), was also reported.

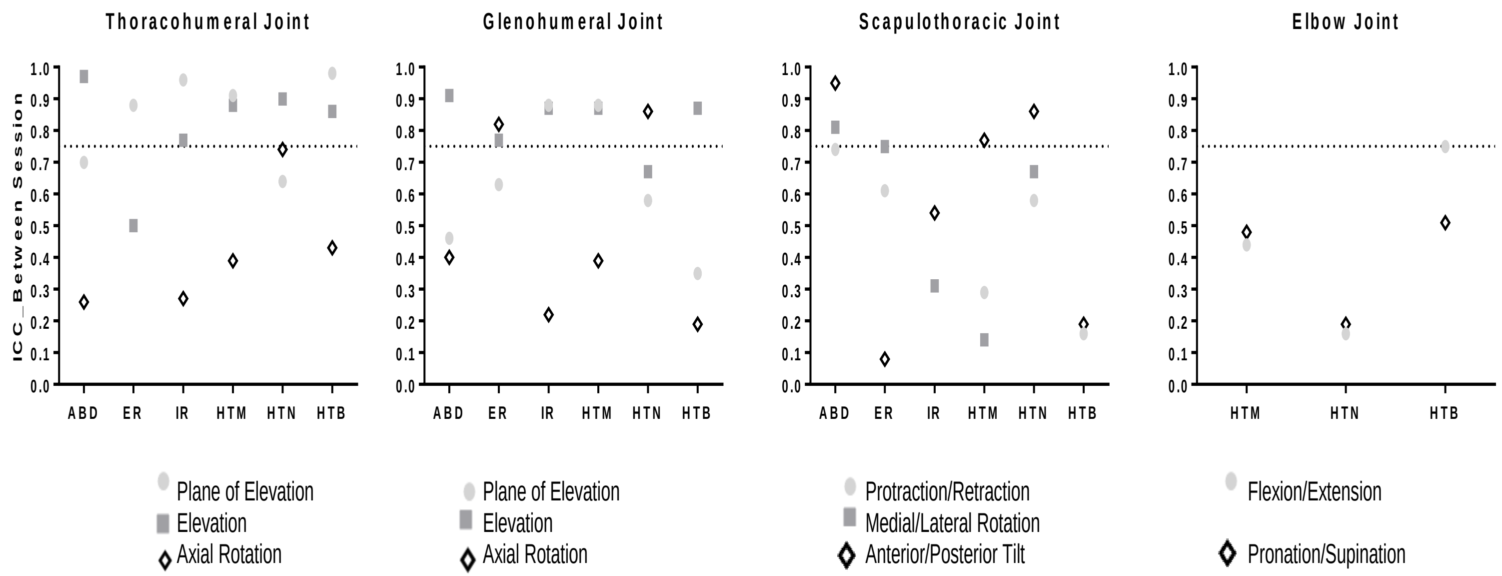
The following sections describe the test-retest reliability results for each task. Figures 4.1 and 4.2 demonstrate the distribution of ICC for ROM and PTA in all tasks, joints and rotation axes. Thereafter, each section refers to the relevant tables and figures detailing results for specific tasks.



ABD - Abduction; ER - External Rotation ; IR - Internal Rotation; HTM - Hand to Mouth; HTN - Hand to Neck; HTB - Hand to Back
Data not reported due to *negative Cronbach's Alpha in ER Glenohumeral Elevation & HTN* Elbow Joint Pronation/Supination

ICC – Intraclass correlation coefficient

Figure 4.1: Inter-Session intraclass correlation coefficients for each joint during each task for ROM (n=11)



ABD - Abduction; ER - External Rotation ; IR - Internal Rotation; HTM - Hand to Mouth; HTN - Hand to Neck; HTB - Hand to Back
Data not reported due to *negative Cronbach's Alpha in* ER Thoracohumeral axial rotation; IR & HTB Scapulothoracic protraction/retraction.

ICC – Intraclass correlation coefficient

Figure 4.2: Inter-Session intraclass correlation coefficients for each joint, during each task for point of task achievement (n=11)

4.4.2 Test-retest reliability of the Abduction Task

The B&A plots suggested no consistent bias between the two measurements with a wide scatter of data evident for individuals in the Abduction Task (Figures 4.3 and 4.4). The 95% LOA were wide. ST A/P tilt had the narrowest LOA in both ROM (-12º to 6.8º) and PTA (-9.6º to 19º). TH/GH AR had the widest LOA for PTA (TH AR -73º to 66º) and ROM (GH AR -33º to 24º). The majority of rotation axes demonstrated variation in both ROM achieved and difference between the two time points. Apart from one outlier, TH elevation had the smallest variability in differences both in ROM (-0.97º to -6.38º) and PTA (0.95º to 10.98º). There were no obvious trends in either ROM or PTA achieved or differences between time 1 and 2.

The majority of rotation axes achieved an acceptable ICC of >0.75 for both ROM and PTA (Table 4.5). The SEM values ranged from 3.5º to 20º with 13/18 variables being <10º. TH joint had both the highest recorded reliability coefficient for elevation at PTA (ICC 0.97; SEM 6.3º) and the lowest for AR at PTA (ICC 0.26; SEM 20º). Except for ROM of ST P/R, the ST joint demonstrated acceptable reliability for the other rotation axes ST A/P and M/L in both ROM and PTA, with ICCs ranging from 0.79 to 0.95; SEM 6.1º to 8.8º.

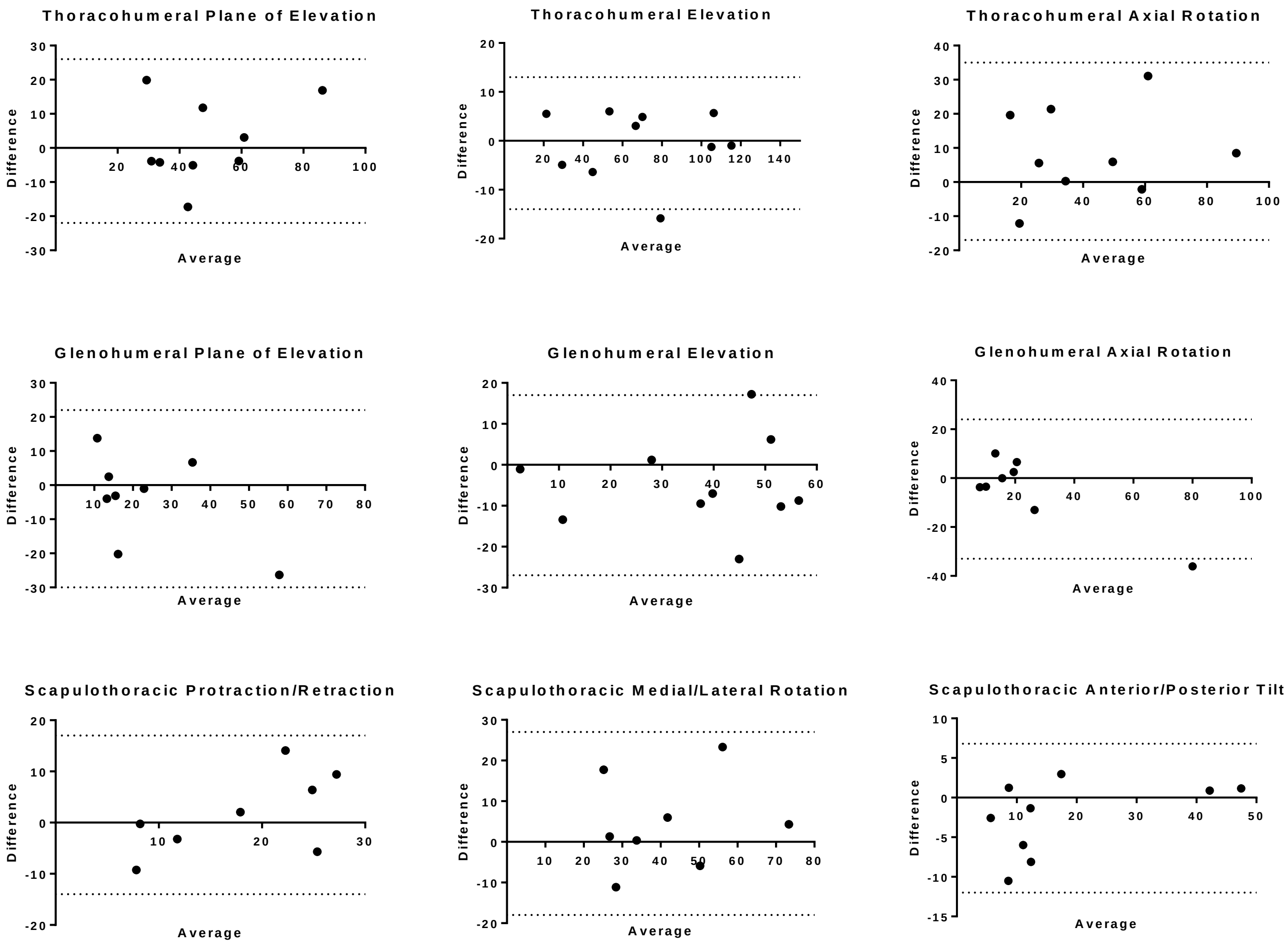


Figure 4.3: Bland and Altman plots for ROM for Abduction Task

Units of measurement: Degrees; Mean of Measures 95% Limits of Agreement (LOA) Individual

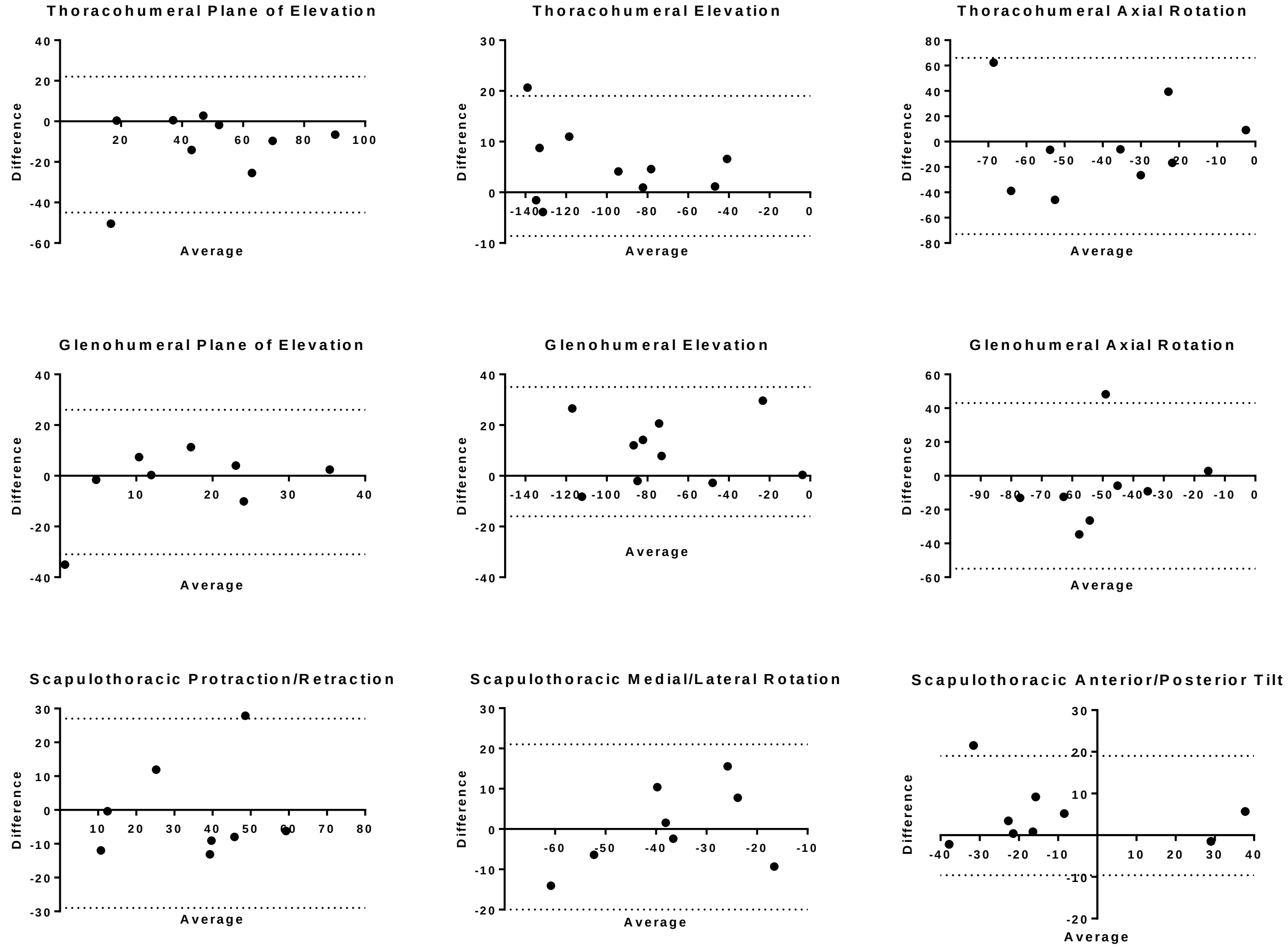


Figure 4.4: Bland and Altman plots for point of task achievement for Abduction Task

Units of measurement: Degrees; Mean of Measures 95% Limits of Agreement (LOA) Individual

Table 4.5: Test-retest reliability of kinematic and spatiotemporal parameters for the Abduction Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); ": negative ICC recorded; +: negative Cronbach's Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	Mean(SD)	SEM Degrees	MDC	ICC	ICC 95% CI	Mean Difference	SD Difference	95% LOA Degrees
Thoracohumeral Joint								
ROM Plane of Elevation	48.3(18.1)	**7.8**	21.6	**0.82**	0.41→0.96	1.9	12	-22→26
ROM Elevation	69.2(32.7)*	**4.7**	13.1	**0.98**	0.92→0.99	-.42	7.1	-14→13
ROM Axial Rotation	42.7(24)	**10.3**	28.5	**0.82**	0.41→0.95	8.7	13	-17→35
PTA Plane of elevation	45.1(24.1)*	**13.5**	37.3	**0.70**	0.16→0.96	-12	17	-45→22
PTA Elevation	-118.4(54.8)*	**6.3**	17.5	**0.97**	0.91→0.99	5.2	7.1	-8.6→19
PTA Axial Rotation	-40.1(23.3)	**20**	55.4	**0.26**	0-.41→0.76	-3.3	36	-73→66
Glenohumeral Joint								
ROM Plane of Elevation	23.2(17)*	**8.6**	23.7	**0.72**	0.14→0.93	-4	13	-30→22
ROM Elevation	37.1(18.7)	**7.9**	22.4	**0.81**	0.44→0.95	-4.8	11	-27→17
ROM Axial Rotation	24.2(23.7)	**9.9**	21.8	**0.83**	0.41→0.96	-4.6	15	-33→24
PTA Plane of elevation	16.5(12.1)	**8.9**	24.8	**0.46**	-0.26→0.86	-2.7	15	-31→26
PTA Elevation	-70.1(38.2)	**11.5**	32	**0.91**	0.69→0.98	9.8	13	-16→35
PTA Axial Rotation	-48.9(20)	**15.4**	42.7	**0.40**	-0.32→0.84	-6.3	25	-55→43
Scapulothoracic Joint								
ROM Protraction/Retraction	18.2(8)	**4.9**	13.4	**0.63**	-0.02→0.91	1.7	7.9	-14→17
ROM Medial/Lateral Rotation	41.9(17)	**7.8**	21.5	**0.79**	0.31→0.95	4.5	11	-18→27
ROM Anterior/Posterior Tilt	18.4(15.4)	**3.5**	9.8	**0.95**	0.80→0.99	-2.5	4.7	-12→6.8
PTA Protraction/Retraction	35.1(17.4)	**8.8**	24.4	**0.79**	0.20→0.94	-1.1	14	-29→27
PTA Medial/Lateral Rotation	-36.7(14.8)	**6.5**	18	**0.81**	0.35→0.96	.39	10	-20→21
PTA Anterior/Posterior Tilt	-8.1(27.3)	**6.1**	16.9	**0.95**	0.81→0.99	4.7	7.3	-9.6→19
Duration of Task (Seconds)	1.53(0.67)*	**0.14**	0.40	**0.93**	0.75→0.98	0	0.22	-0.43→0.44

4.4.3 Test-retest reliability of the External Rotation Task

B&A plots for the External Rotation Task demonstrated no consistent bias between measurement at time 1 and 2 (Figures 4.5 and 4.6). In GH elevation a trend for increased difference recorded with rising ROM was seen. Wide LOA were observed although outliers influenced the spread. For this task two participants (Participants 9 & 8) were responsible for the outlying values. The ROM had narrower LOA compared with PTA.

For this task five variables achieved an acceptable reliability coefficient i.e. ICC >0.75 (Figures 4.1 and 4.2 and Table 4.6). Only one of these variables, ST P/R at PTA, had an acceptable SEM of 6.2º. The four other variables either had SEM values >10º or greater than half mean ROM recorded (ST M/L rotation mean range 8.1º with SEM 5.8º). Therefore, according to this research's reliability parameters, two variables achieved acceptable reliability; GH elevation and ST M/L rotation at PTA. GH elevation (ROM) generated a negative ICC -0.48; SEM 15.05º while TH elevation (ROM) and AR (PTA) had a negative Cronbach's alpha, both of which indicate a lack of internal consistency. Therefore, ICC and SEM were not reported for this variable. Both results suggested no correlation between measures at the two time points. The range and spread of data may have been too small to generate accurate reliability results.

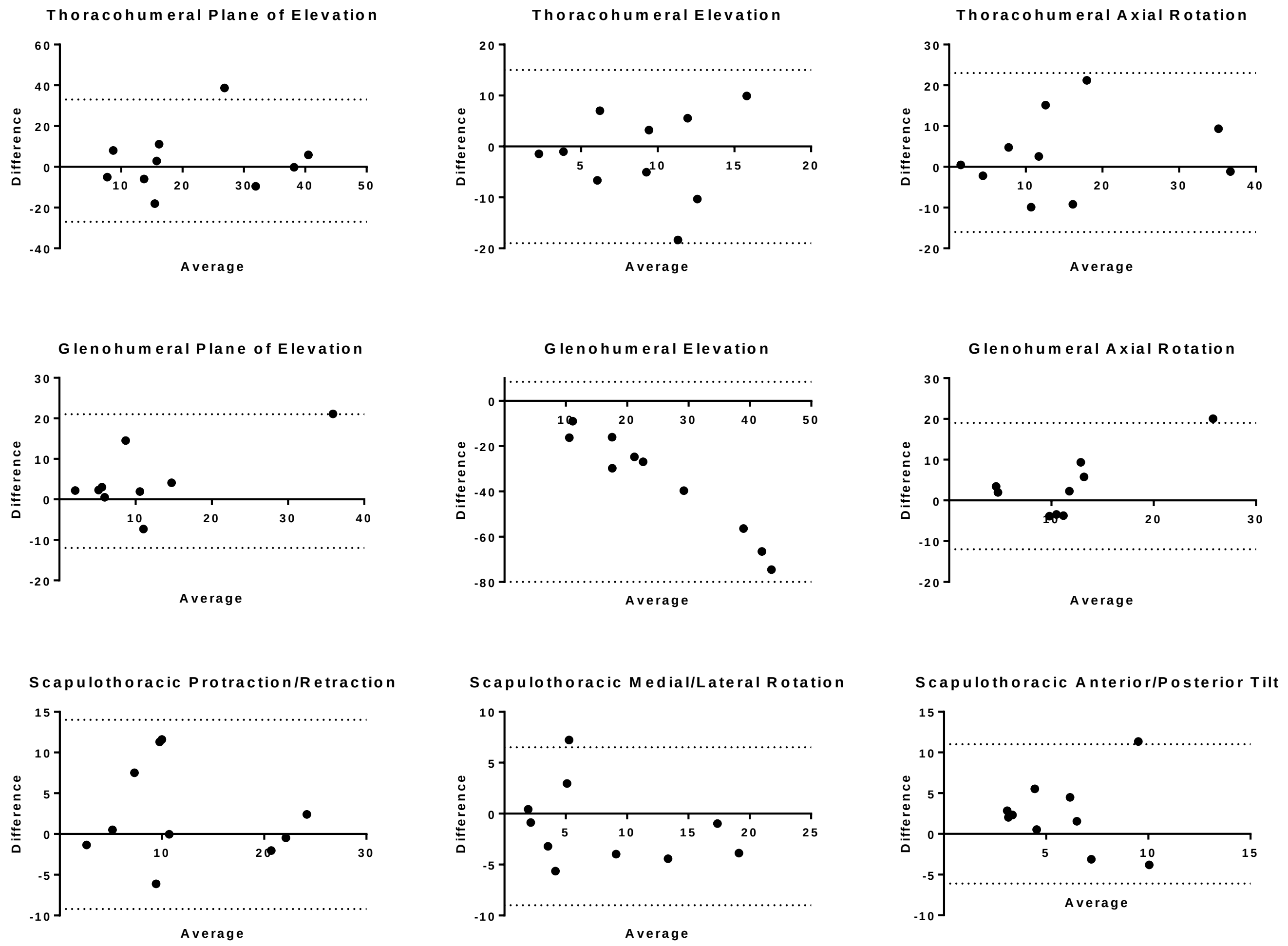


Figure 4.5: Bland and Altman plots for ROM for External Rotation Task

Units of measurement: Degrees: Mean of Measures 95% Limits of Agreement (LOA) Individual

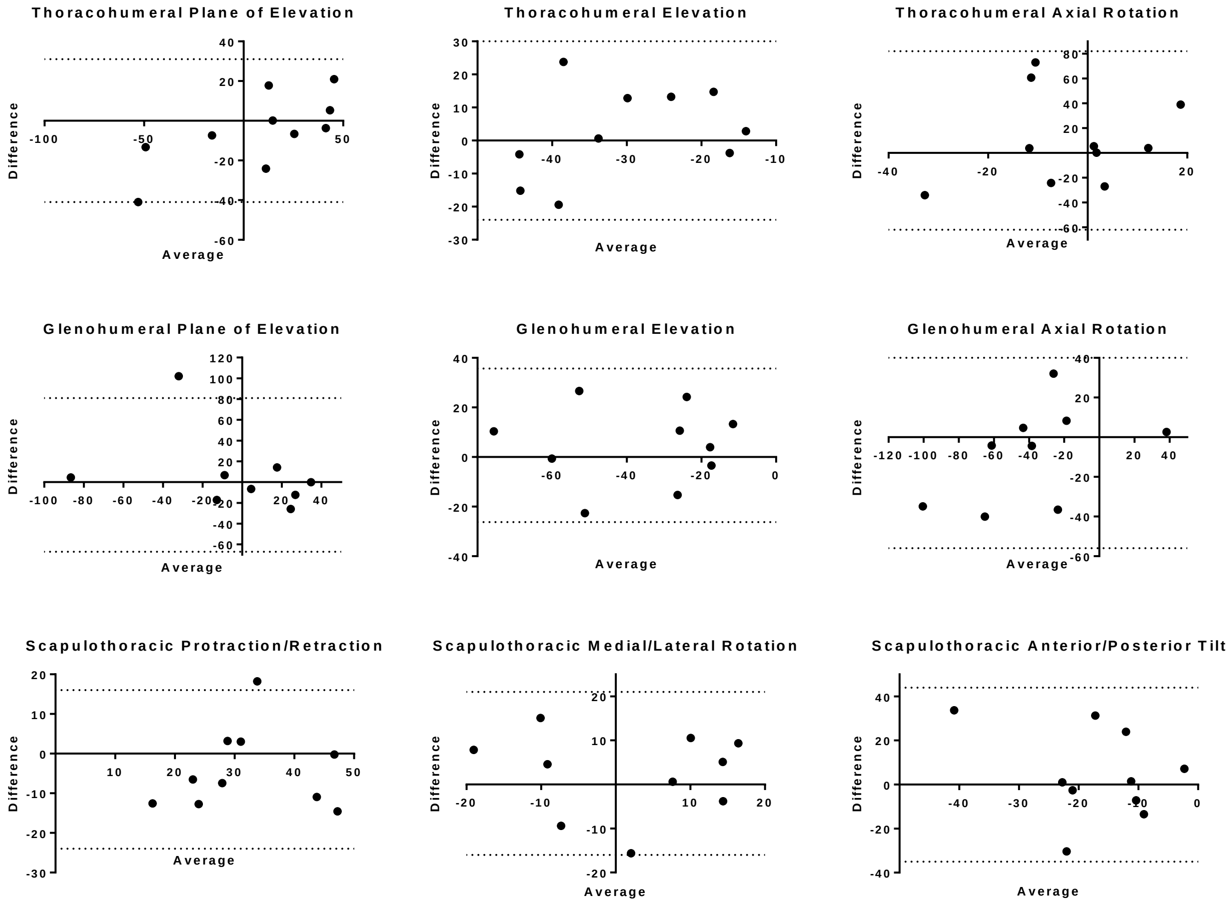


Figure 4.6: Bland and Altman plots for point of task achievement for External Rotation Task

Units of measurement: Degrees; Mean of Measures ——— 95% Limits of Agreement (LOA) ············ Individual ●

Table 4.6: Test-retest reliability of kinematic and spatiotemporal parameters for the External Rotation Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); ": negative ICC recorded; +: negative Cronbach's Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	Mean(SD)	SEM Degrees	MDC	ICC	ICC 95% CI	Mean Difference	SD Difference	95% LOA
Thoracohumeral Joint								
ROM Plane of Elevation	21.5(12)	**8.9**	24.7	**0.44**	-0.19→0.82	2.8	15	-27→33
ROM Elevation	8.9(4.2)*	**+**	+	**+**	+	-1.7	8.7	-19→15
ROM Axial Rotation	15.5(11.9)*	**6.5**	17.9	**0.40**	0.20→0.92	3.1	9.9	-16→33
PTA Plane of elevation	7.6(36.1)	**12.5**	34.6	**0.88**	0.61→0.97	-5.2	18	-41→31
PTA Elevation	-33.8(14.4)*	**8.2**	22.6	**0.5**	0.12→0.85	2.5	14	-24→30
PTA Axial Rotation	-7.4(12.9)*	**+**	+	**+**	+	10	37	-62→82
Glenohumeral Joint								
ROM Plane of Elevation	11.1(10.13)*	**5.9**	16.4	**0.66**	0.08→0.93	4.7	8.3	-12→21
ROM Elevation	25.4(12.4)	**15.1**	41.7	**"**	"	-36	23	-80→8.4
ROM Axial Rotation	11.6(6.2)*	**4.8**	13.3	**0.40**	-0.27→0.82	3.5	7.7	0.12→19
PTA Plane of elevation	-3.6(37.9)	**23.2**	64.2	**0.63**	0.03→0.9	7.3	38	-67→81
PTA Elevation	-25.8(34.7)*	**10.4**	28.9	**0.77**	0.34→0.94	4.7	15.8	-26→36
PTA Axial Rotation	-37.7(38.3)	**16.4**	45.4	**0.82**	0.42→0.96	-8	24	-56→40
Scapulothoracic Joint								
ROM Protraction/Retraction	12.2(7.5)	**4**	11	**0.72**	0.23→0.92	2.3	5.9	-9→21.4
ROM Medial/Lateral Rotation	8.1(6.4)	**5.8**	16	**0.82**	0.47→0.95	-1.2	3.9	-9→6.5
ROM Anterior/Posterior Tilt	5.8(2.5)	**2.5**	6.8	**0.07**	-0.53→0.64	4.3	4.3	-6.1→11
PTA Protraction/Retraction	32.3(10.6)	**6.7**	18.4	**0.61**	0.04→0.88	-4.1	10	-24→16
PTA Medial/Lateral Rotation	1.9(12.5)	**6.2**	17.3	**0.75**	0.31→0.93	2.4	9.6	-16→21
PTA Anterior/Posterior Tilt	-16.9(10.7)	**10.3**	28.4	**0.08**	0.53→0.64	4.5	20	-35→44
Duration of Task (Seconds)	0.99(0.18)*	**0.19**	0.52	**"**	"	-0.25	0.32	-0.87→0.38

4.4.4 Test-retest reliability of the Internal Rotation Task

B&A plots calculated for both ROM and PTA in all joints and rotation axes demonstrated no consistent bias in measurement with a random scatter evident in all plots (Figures 4.7 and 4.8). Wide LOA showed that considerable discrepancies existed between the two time points. Outliers were present for both variables impacting on overall LOA, participant 7 being responsible for the largest outliers in this task (Figure 4.7). For ROM all differences in TH elevation were <5º except for an outlier of 12º and <7º in ST M/L rotation with the exception of one outlier of 19º.

This task had variable reliability across all joints and rotation axes (Table 4.7). AR, the key axis of this task, was not reliable for PTA in neither the TH nor GH joints. However, ROM of GH AR recorded an acceptable ICC 0.86 and SEM 7.1º. TH and GH POE and elevation at PTA recorded acceptable reliability coefficients, ICC >0.75, with SEM <9º. The corresponding variables in ROM generated lower ICCs but SEM values were low at ≤3º in TH/GH elevation and ranged from 9.2º to 12.2º in TH/GH POE. Overall, no ST joint rotation axis was reliable for this task. A negative Cronbach's alpha was recorded for ST P/R for both PTA and ROM suggesting a lack of internal consistency. Neither ICC nor SEM were reported for these variables.

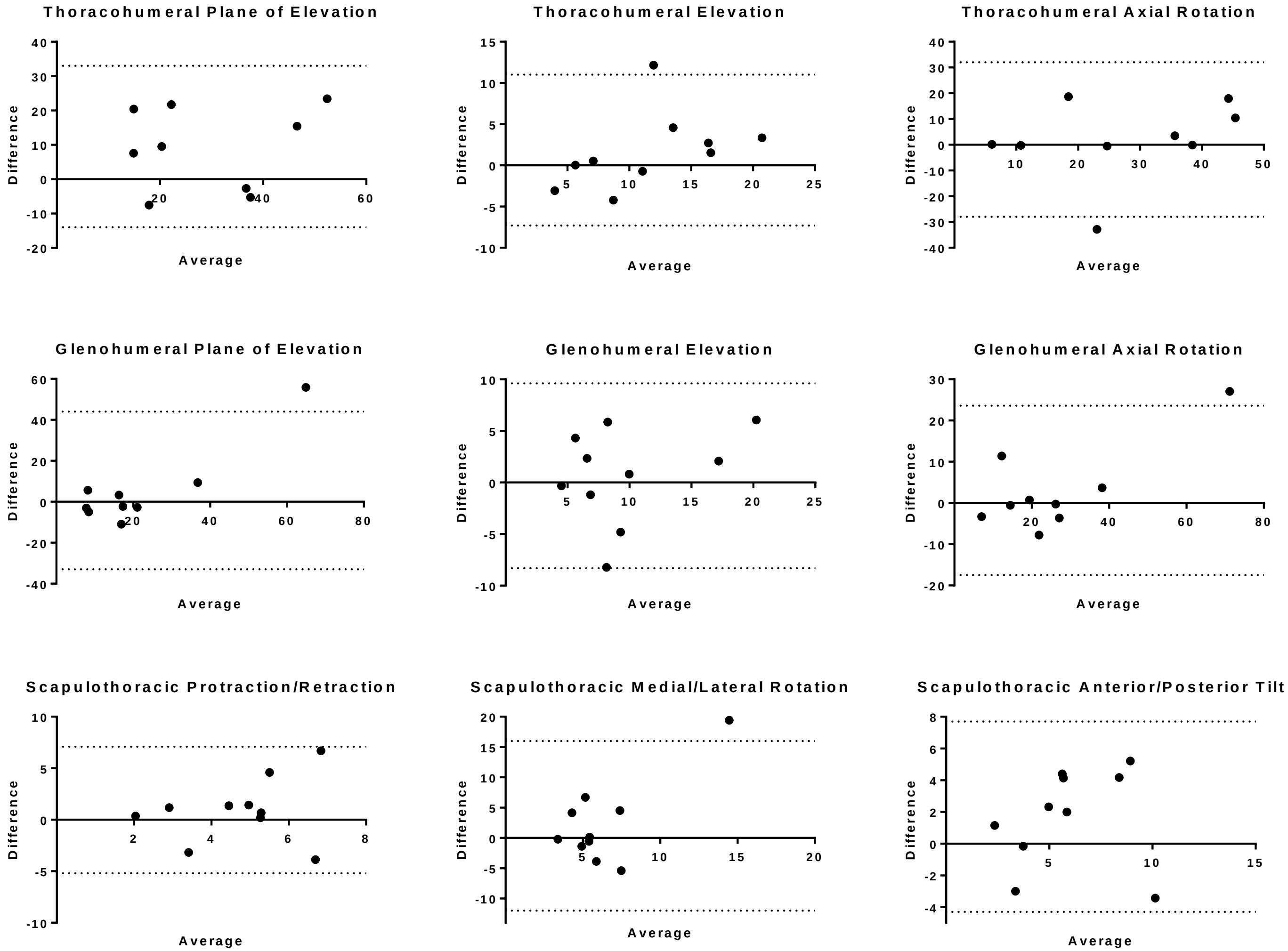


Figure 4.7: Bland and Altman plots for ROM for Internal Rotation Task

Units of measurement: Degrees: Mean of Measures *95% Limits of Agreement (LOA)* *Individual*

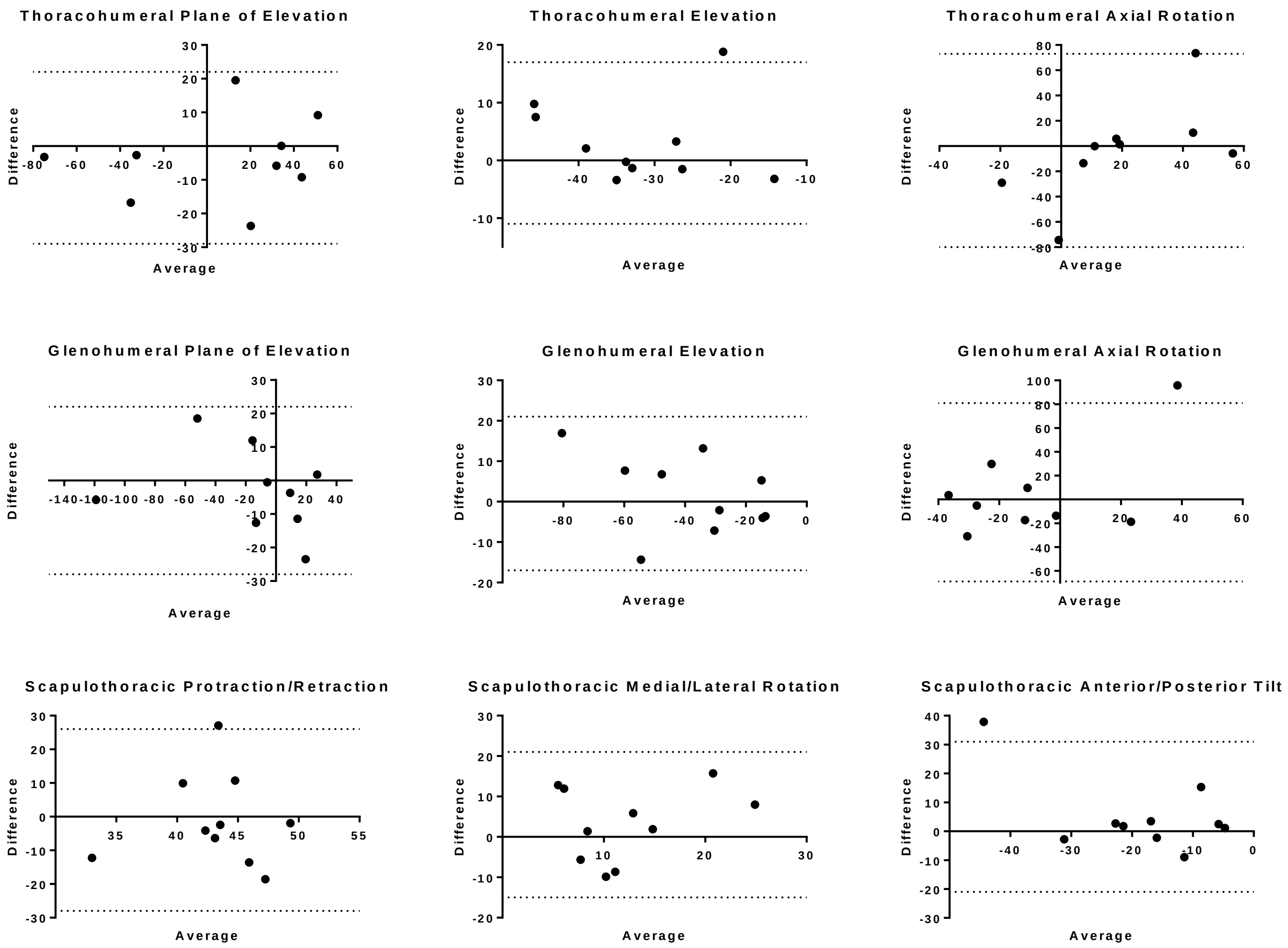


Figure 4.8: Bland and Altman plots for point of task achievement for the Internal Rotation Task

Units of measurement: Degrees: Mean of Measures 95% Limits of Agreement (LOA) Individual

Table 4.7: Test-retest reliability of kinematic and spatiotemporal parameters for Internal Rotation Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); “: negative ICC recorded; +: negative Cronbach’s Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	Mean(SD)	SEM Degrees	MDC	ICC	ICC 95% CI	Mean Difference	SD Difference	95% LOA
Thoracohumeral Joint								
ROM Plane of Elevation	29.3(14.3)	**9.2**	25.5	**0.59**	-0.03→0.89	9.2	12	-14→33
ROM Elevation	27.4(14.3)	**3**	8.4	**0.68**	0.16→0.91	1.7	4.6	-7.6→11
ROM Axial Rotation	4.7(1.6)	**9.1**	25.3	**0.60**	0.20→0.89	1.9	15	-28→32
PTA Plane of elevation	5.7(43.1)	**8.8**	24.5	**0.96**	0.84→0.99	-3.6	13	-29→22
PTA Elevation	-33.3(11.5)	**4.9**	13.6	**0.77**	0.33→0.94	3.2	7	-11→17
PTA Axial Rotation	19.9(24.2)	**20.7**	57.4	**0.27**	-0.41→0.77	-3.5	39	-80→73
Glenohumeral Joint								
ROM Plane of Elevation	22(18.4)*	**12.2**	33.8	**0.56**	-0.07→0.88	5.6	20	-33→44
ROM Elevation	9.7(5.1)*	**2.9**	7.9	**0.69**	0.18→0.91	0.69	4.6	-8.3→9.6
ROM Axial Rotation	26.4(19.5)	**7.1**	19.6	**0.86**	0.54→0.97	3.03	10.5	-17.5→23.6
PTA Plane of elevation	-5.7(29.8)	**8.7**	24	**0.96**	0.86→0.99	-2.8	13	-28→22
PTA Elevation	-32.2(34.5)	**6.5**	18	**0.92**	0.71→0.98	1.9	9.7	-17→21
PTA Axial Rotation	-8.7(25.3)	**20.9**	58.9	**0.32**	-0.36→0.79	5.9	38	-69→81
Scapulothoracic Joint								
ROM Protraction/Retraction	5.1(1.8)*	**+**	+	**+**	+	.94	3.1	-5.2→7.1
ROM Medial/Lateral Rotation	7.3(4.2)	**3**	8.3	**0.48**	-0.14→0.84	2.3	7.1	-12→16
ROM Anterior/Posterior Tilt	5.9(2.5)	**2**	5.5	**0.39**	-0.25→0.80	1.7	3.1	-4.3→7.7
PTA Protraction/Retraction	45.31(4.42)	**+**	+	**+**	+	-1.1	14	-28→26
PTA Medial/Lateral Rotation	12.24(6.37)	**5.3**	14.7	**0.31**	-0.33→0.76	3.3	9.1	-15→21
PTA Anterior/Posterior Tilt	-18.3(12.31)	**8.3**	23.1	**0.54**	-0.06→0.86	5.1	13	-21→31
Duration of Task (Seconds)	0.89(0.31)	**0.16**	0.45	**0.56**	-0.34→0.87	-0.13	0.24	-0.59→0.39

4.4.5 Test-retest reliability of the Hand-to-Mouth Task

The B&A plots for both ROM and PTA in the Hand-to-Mouth Task demonstrated no consistent bias (Figures 4.9 and 4.10). Wide LOA were present, none <10º, with PTA variables demonstrating wider LOA than ROM. However, one outlier (Participant 7) of 24º in TH POE (ROM) impacted on these LOA as most differences in this rotation axis were <10º (Figure 4.9). Apart from one participant all moved more at time 1 than time 2 in this TH POE. Large variation in magnitude of ROM was evident except for AR ROM which clustered round 10º to 20º (Figure 4.9), although differences of <20º between time 1 and 2 were evident except for two outliers (30º and 64º: Participant 2 and 7 respectively).

For GH AR at PTA (Figure 4.10) larger variation in magnitude of ROM was evident but with a similar degree of difference except for one outlier of 67º. Outliers were present across the rotation axes but no single participant was responsible. Elbow P/S for both ROM and PTA presented with wide LOA and large differences between time 1 and time 2 suggesting poor reliability.

This task had varying reliability (ICC 0.14 to 0.91; SEM 3.1º to 23º) with no joint demonstrating consistent reliability across all rotation axes (Table 4.8). In ROM, only two variables had acceptable reliability ST M/L rotation (ICC 0.79, SEM 3.3º) and elbow F/E (ICC 0.77, SEM 8.3º). Five variables at PTA had acceptable reliability, GH and TH POE (ICC 0.88, SEM 6.2º; ICC 0.91, SEM 3.9º) and elevation (ICC 0.87, SEM 9.4º; ICC 0.88, SEM 7.2º) and ST A/P tilt (ICC 0.77, SEM 7.5º).

Inter-session SEM values reflected the variable ICC scores with a broad spread from 3.1º in ST A/P tilt (ROM) to 23º in elbow P/S (PTA). The majority of variables had SEM <10º regardless of an acceptable ICC or not. However, when evaluating SEM it is important to take note of actual ROM recorded. A low SEM over a small ROM would not be as reliable as an equivalent error over a large ROM. This was particularly evident at the ST joint where all SEM were <4º but for ST P/R this error represented nearly half actual ROM recorded.

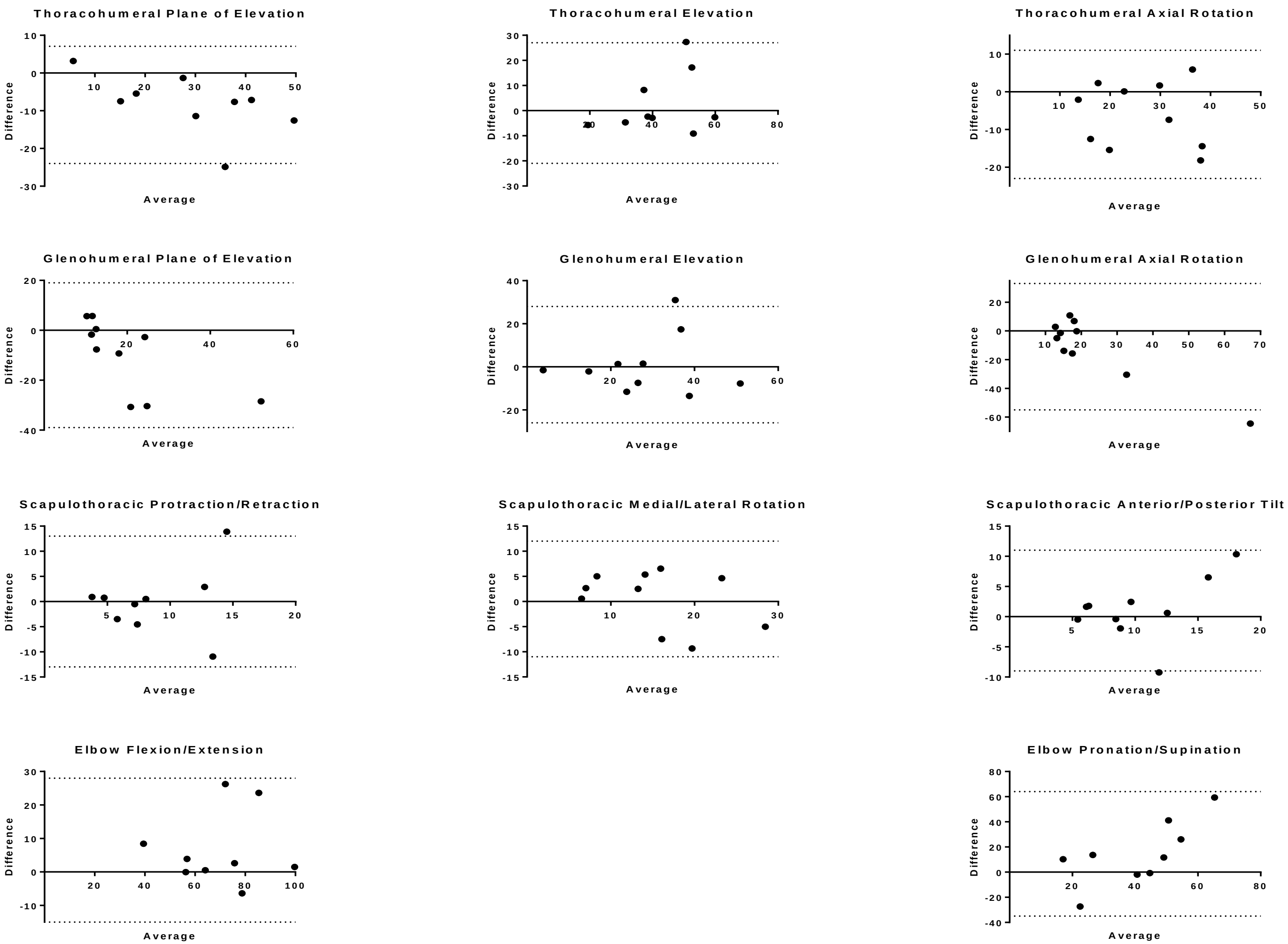


Figure 4.9: Bland and Altman plots for ROM for Hand-to-Mouth Task

Units of measurement: Degrees; Mean of Measures —— *95% Limits of Agreement (LOA)* ············ *Individual* ●

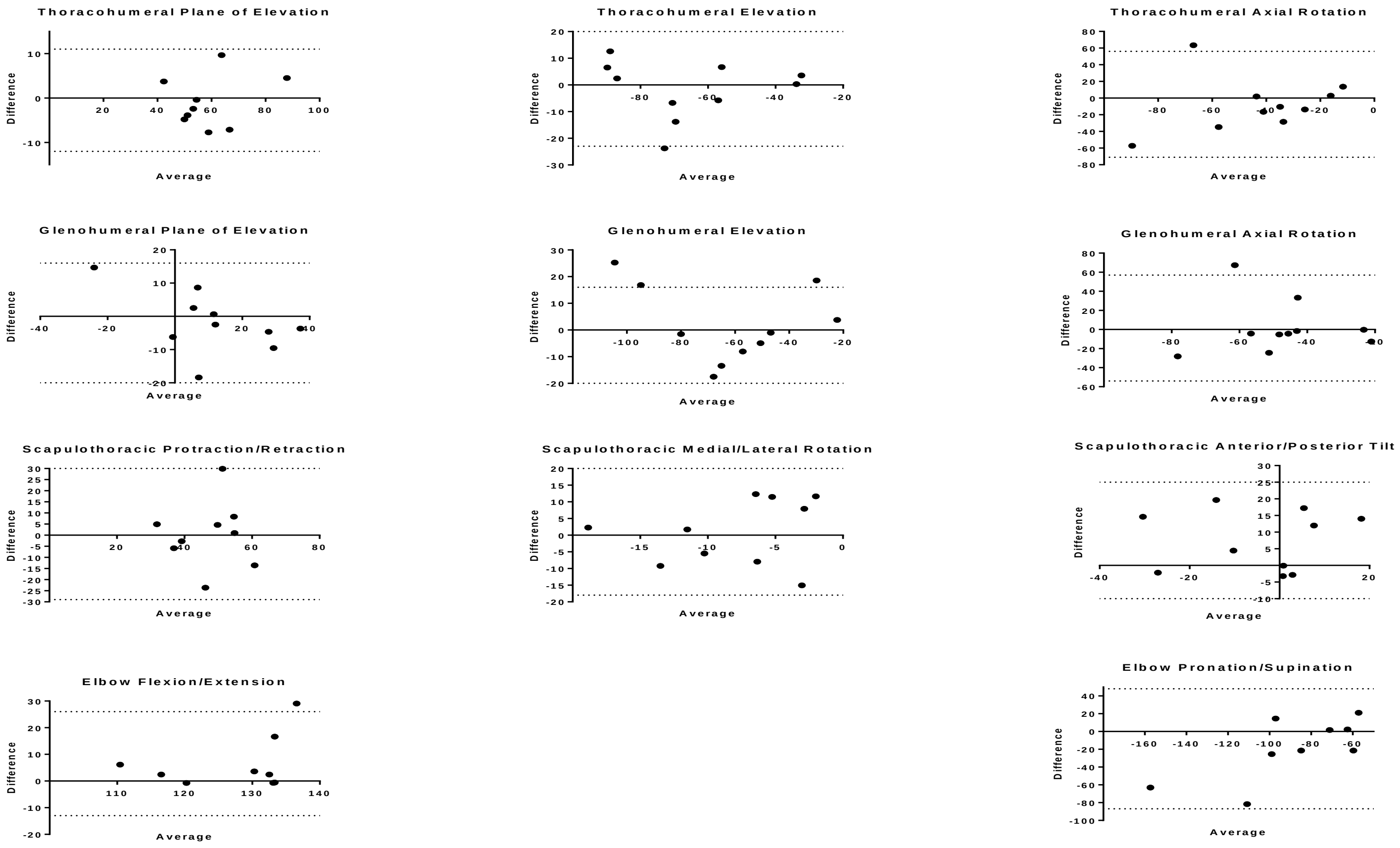


Figure 4.10: Bland and Altman plots for point of task achievement for Hand-to-Mouth Task

Units of measurement: Degrees; Mean of Measures ——— *95% Limits of Agreement (LOA)* ++++++++++++ *Individual* ●

Table 4.8: Test-retest reliability of kinematic and spatiotemporal parameters for the Hand-to-Mouth Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); “: negative ICC recorded; +: negative Cronbach’s Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	Mean(SD)	SEM Degrees	MDC	ICC	ICC 95% CI	Mean Difference	SD Difference	95% LOA
Thoracohumeral Joint								
ROM Plane of Elevation	28.4(13.7)	**7.2**	19.8	**0.73**	0.21→0.93	-8.3	7.9	-24→7.1
ROM Elevation	40.9(15.4)*	**9.2**	25.5	**0.64**	0.06→0.91	2.8	12	-21→27
ROM Axial Rotation	26.5(9.5)	**6.3**	17.6	**0.56**	-0.04→0.87	-6	8.7	-23→11
PTA Plane of elevation	58.7(13.2)	**3.9**	10.7	**0.91**	0.69→0.98	-.93	5.9	-12→11
PTA Elevation	-70.1(27.2)*	**7.2**	19.9	**0.88**	0.62→0.97	-1.8	11	-23→20
PTA Axial Rotation	-42.1(23.8)	**18.7**	51.8	**0.39**	-0.25→0.80	-7.9	32	-71→56
Glenohumeral Joint								
ROM Plane of Elevation	15.3(11.6)*	**10**	27.7	**0.38**	-0.26→0.94	-9.9	15	-39→19
ROM Elevation	28(13.3)	**8.3**	23	**0.61**	0.05→0.89	0.72	14	-26→28
ROM Axial Rotation	22.6(16.7)	**13.7**	38.1	**0.32**	-0.32→0.77	-11	22	-55→33
PTA Plane of elevation	11.3(17.4)	**6.2**	17.1	**0.88**	0.6→0.97	-1.8	9.3	-20→16
PTA Elevation	-61.9(26.3)	**9.4**	25.9	**0.87**	0.6→0.97	1.8	14	-26→30
PTA Axial Rotation	-47.2(16.9)	**14.9**	41.3	**0.22**	-0.41→0.72	1.9	28	-54→57
Scapulothoracic Joint								
ROM Protraction/Retraction	8.6(4)*	**3.5**	9.7	**0.23**	-0.44→0.75	-0.06	6.7	-13→13
ROM Medial/Lateral Rotation	15.3(7.1)*	**3.3**	9	**0.79**	0.28→0.93	0.54	5.7	-11→12
ROM Anterior/Posterior Tilt	10.3(4.2)*	**3.1**	8.5	**0.48**	-0.14→0.84	1.1	5.1	-9→11
PTA Protraction/Retraction	47.3(9.6)	**8**	22.3	**0.29**	-0.38→0.78	0.32	15	-29→30
PTA Medial/Lateral Rotation	-8(5.4)	**5**	14	**0.14**	-0.49→0.68	0.97	9.9	-18→20
PTA Anterior/Posterior Tilt	-4.6(15.5)	**7.5**	20.8	**0.77**	0.33→0.94	7.4	9.1	-10→25
Elbow Joint								
ROM Flexion/Extension	69.8(17.9)	**8.3**	22.9	**0.77**	0.34→0.95	6.7	11	-15→28
ROM Pronation/Supination	41.2(16.1)	**15**	41.5	**0.14**	-0.51→0.70	15	25	-35→64
PTA Flexion/Extension	127.4(9.2)	**6.9**	19.1	**0.44**	-0.23→0.84	6.5	10	-13→26
PTA Pronation/Supination	-88.9(32.1)	**23**	63.8	**0.48**	0.18→0.85	-19	35	-87→48
Duration of Task (Seconds)	1.15(.38)*	**0.25**	0.68	**0.5**	-0.14→0.85	-0.17	0.39	-0.92→0.59

4.4.6 Test-retest reliability of the Hand-to-Neck Task

As with previous tasks the Hand-to-Neck Task B&A plots demonstrated no consistent bias, wide LOA and large differences between measurement sessions for most joints and rotation axes (Figures 4.11 and 4.12). While a few outliers were present large differences between time 1 and 2 were evident across participants contributing to wide LOA. For PTA, the widest LOA was seen in elbow P/S (-77º to 64º) and narrowest in GH AR (-18º to 25º). Conversely for ROM, GH AR had the widest LOA (-48º to 36º) while ST P/R the narrowest (-10º to 30º). However, compared with other tasks the ST joint had the widest LOA ranging from -37º to 33º across the three rotation axes in this task. Elbow P/S was the least reliable, with LOA from -97º to 64º.

The TH joint had the highest ICCs ranging from 0.64 to 0.90 with SEM between 6.9º and 15.8º (Table 4.9). However, only two ICCs were above the acceptable reliability coefficient of 0.75. The ST joint demonstrated the next highest ICCs 0.58 to 0.86 with SEM from 7.1º to 10.2º. As was evident from B&A plots the largest SEM values for ST joint rotation axes were seen in this task. This coincided with larger ROM recorded and observed variability in task performance. For this task the GH joint had only one variable with an acceptable reliability coefficient (GH elevation at PTA: ICC 0.90; SEM 8.4º). The elbow joint recorded low ICCs with relatively high SEM values (ICC 0.16 to 0.56; SEM 11º to 21.4º). A negative ICC was recorded for elbow P/S indicating no correlation between measures at the two time points.

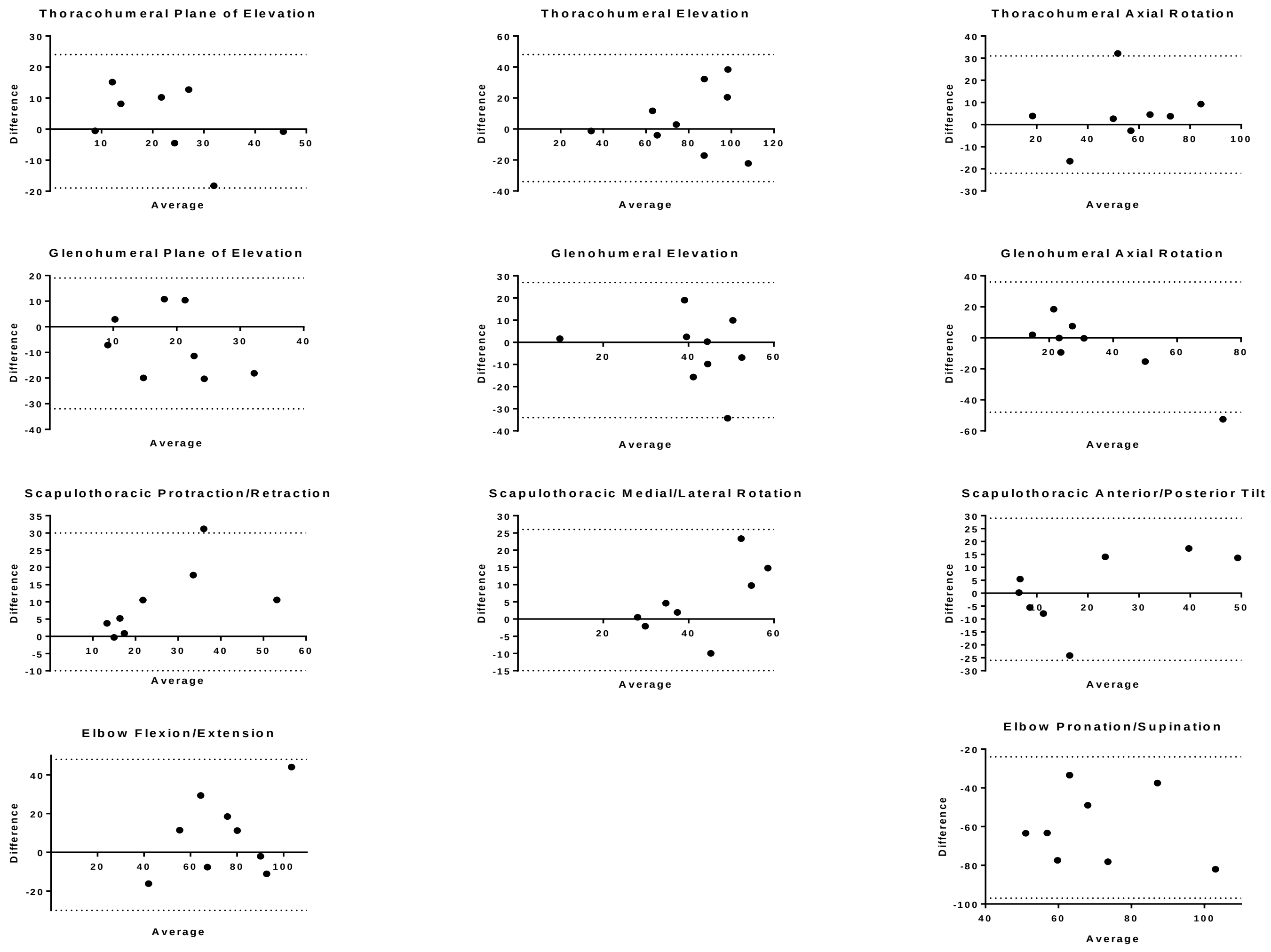


Figure 4.11: Bland and Altman plots for ROM in the Hand-to-Neck Task

Units of measurement: Degrees; Mean of Measures —— 95% Limits of Agreement (LOA) ··········· Individual ●

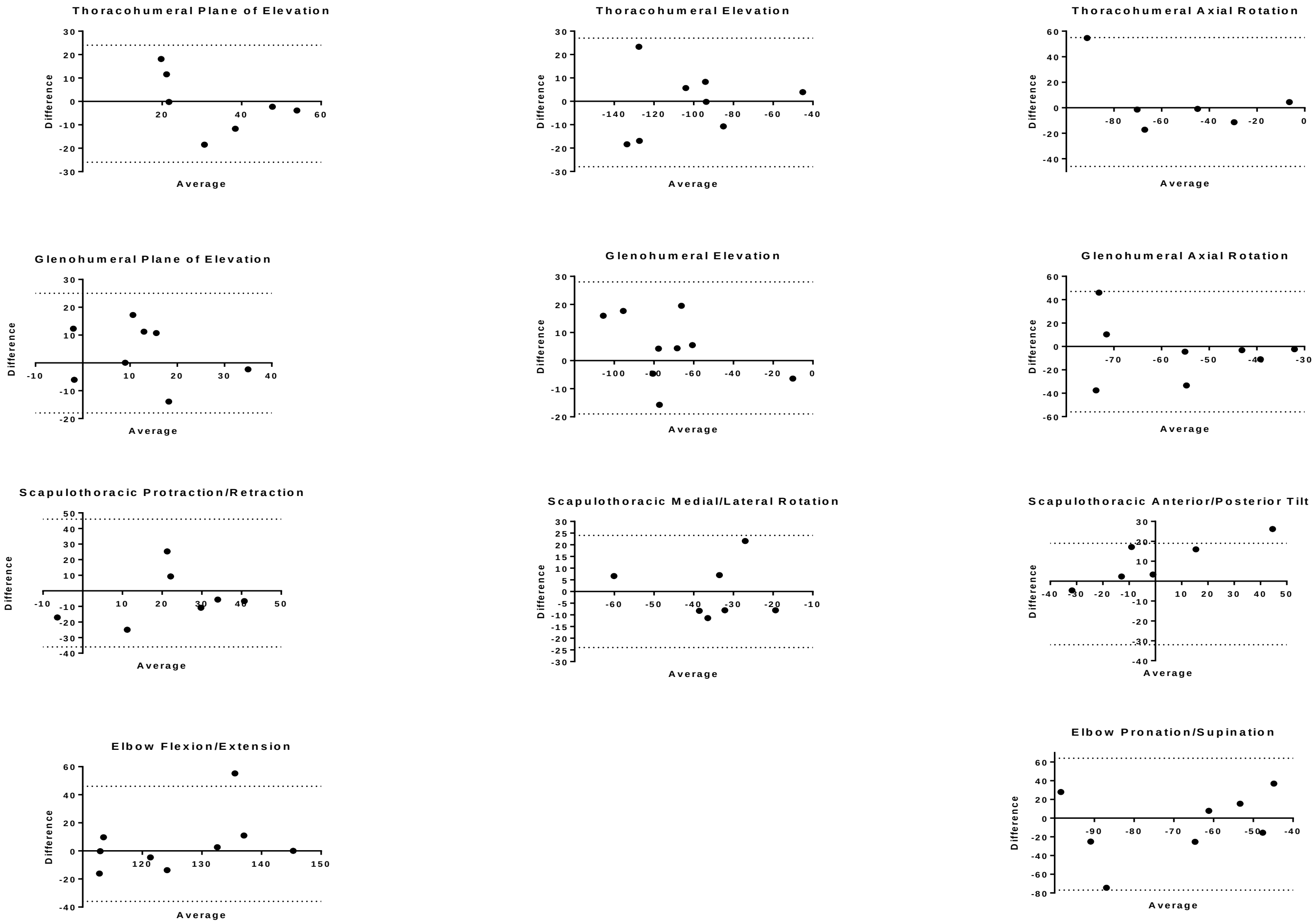


Figure 4.12: Bland and Altman plots for point of task achievement in the Hand-to-Neck Task

Units of measurement: Degrees; Mean of Measures ——— *95% Limits of Agreement (LOA)* ············ *Individual* ●

Table 4.9: Test-retest reliability of kinematic and spatiotemporal parameters for the Hand-to-Neck Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); “: negative ICC recorded; +: negative Cronbach’s Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	**Mean(SD)**	**SEM Degrees**	**MDC**	**ICC**	**ICC 95% CI**	**Mean Difference**	**SD Difference**	**95% LOA**
Thoracohumeral Joint								
ROM Plane of Elevation	23.2(12)	**6.9**	19.2	**0.67**	0.05→0.92	2.8	11	-19→24
ROM Elevation	79.6(22.8)	**13.4**	37	**0.66**	0.08→0.91	6.8	21	-34→48
ROM Axial Rotation	53.9(21)	**9.1**	25.1	**0.81**	0.37→0.96	4.6	14	-22→31
PTA Plane of elevation	33.3(13.6)	**7.6**	21.1	**0.69**	0.04→0.94	-0.98	13	-26→24
PTA Elevation	-99.1(35.8)*	**9.1**	25.3	**0.90**	0.62→0.98	-0.62	14	-28→27
PTA Axial Rotation	-51.6(30.8)	**15.8**	43.7	**0.74**	0.05→0.96	4.7	26	-46→55
Glenohumeral Joint								
ROM Plane of Elevation	19.1(7.7)	**7.3**	20.2	**0.10**	-0.58→0.71	-6.6	13	-32→19
ROM Elevation	41.2(12.7	**9.2**	25.4	**0.48**	-0.18→0.85	-3.7	15	-34→27
ROM Axial Rotation	33.2(19.6	**13**	36.1	**0.56**	0.12→0.89	-6.2	21	-48→36
PTA Plane of elevation	12.2(11.8)	**6.9**	19.2	**0.66**	0.03→0.92	3.7	11	-18→25
PTA Elevation	-71.3(27)	**8.4**	23.3	**0.90**	0.66→0.98	4.5	12	-19→28
PTA Axial Rotation	-55.3(16.3)	**14**	38.7	**0.27**	-0.45→0.79	-4.4	26	-56→47
Scapulothoracic Joint								
ROM Protraction/Retraction	28.51(14)	**8.8**	24.4	**0.60**	-0.06→0.90	10	10	-10→30
ROM Medial/Lateral Rotation	42.6(11.8)*	**7.1**	19.7	**0.64**	-0.01→0.91	5.4	10	-15→26
ROM Anterior/Posterior Tilt	20.3(16.2)	**8.6**	23.9	**0.72**	0.42→0.94	1.7	14	-26→29
PTA Protraction/Retraction	21.8(15.7)	**10.2**	28.2	**0.58**	-0.15→0.91	-4.4	17	-37→29
PTA Medial/Lateral Rotation	-35.3(12.7)	**7.3**	20.2	**0.67**	-0.01→0.93	.0.06	12	-24→24
PTA Anterior/Posterior Tilt	.9(26.4)	**9.9**	27.5	**0.86**	0.37→0.98	10	12	-13→33
Elbow Joint								
ROM Flexion/Extension	75.9(25.7))*	**12.9**	35.8	**0.56**	-0.07→0.88	-61	19	-91→24
ROM Pronation/Supination	70.3(17.3)	**21.4**	59.3	**“**	“	8.6	20	-30→48
PTA Flexion/Extension	126.1(12)	**11**	30.5	**0.16**	-0.49→0.72	4.9	21	-36→46
PTA Pronation/Supination	-68.5(20.8)	**18.8**	52	**0.19**	-0.51→0.76	-6.5	36	-77→64
Duration of Task(Seconds)	1.58(.36)*	**0.23**	0.63	**0.32**	-0.32→0.77	0.04	0.41	-0.77→0.85

4.4.7 Test-retest reliability of the Hand-to-Spine Task

As with all previous tasks, no consistent bias or trend in measurement between time 1and 2 was demonstrated in the B&A plots for the Hand-to-Spine Task (Figures 4.13 and 4.14). Wide LOA across the joints and rotation axes were noted with outliers impacting on results despite clusters of participants with smaller differences seen between time 1 and 2 in some rotation axes. This was evident for ST A/P tilt at PTA where one outlier of 13º skewed the LOA as all other differences were <6º and in GH POE/AR (ROM) an outlier of 160º skewed LOA. Similarly one outlier of 129º in elbow joint P/S at PTA impacted on LOA. Similar to the Hand-to-Neck Task wide LOA were recorded for the ST joint. However, this was mainly for the variable PTA not ROM.

This task had both very low and high ICCs across joints and rotation axes (Table 4.10). Six variables achieved acceptable reliability. However, conflicting results were seen between variables for ROM and PTA across TH and GH joints. ROM of GH POE (ICC 0.91; SEM 9.3º) and AR (ICC 0.91; SEM 8.9º) were acceptable while PTA for these axes was not. Both ROM and PTA for TH POE had acceptable reliability (ICC 0.93; SEM 8º and ICC 0.98; SEM 5.6º respectively). No rotation axis of the ST joint had an acceptable reliability coefficient with ICCs ranging from a negative recording to 0.46. This was in the presence of SEM values of ≤3.5º in ROM although higher SEM values were recorded for PTA. Elbow P/S demonstrated low ICCs and high SEM values as for previous tasks with elbow F/E achieving and acceptable reliability coefficient of ICC 0.75 but SEM >10º at 15.3º.

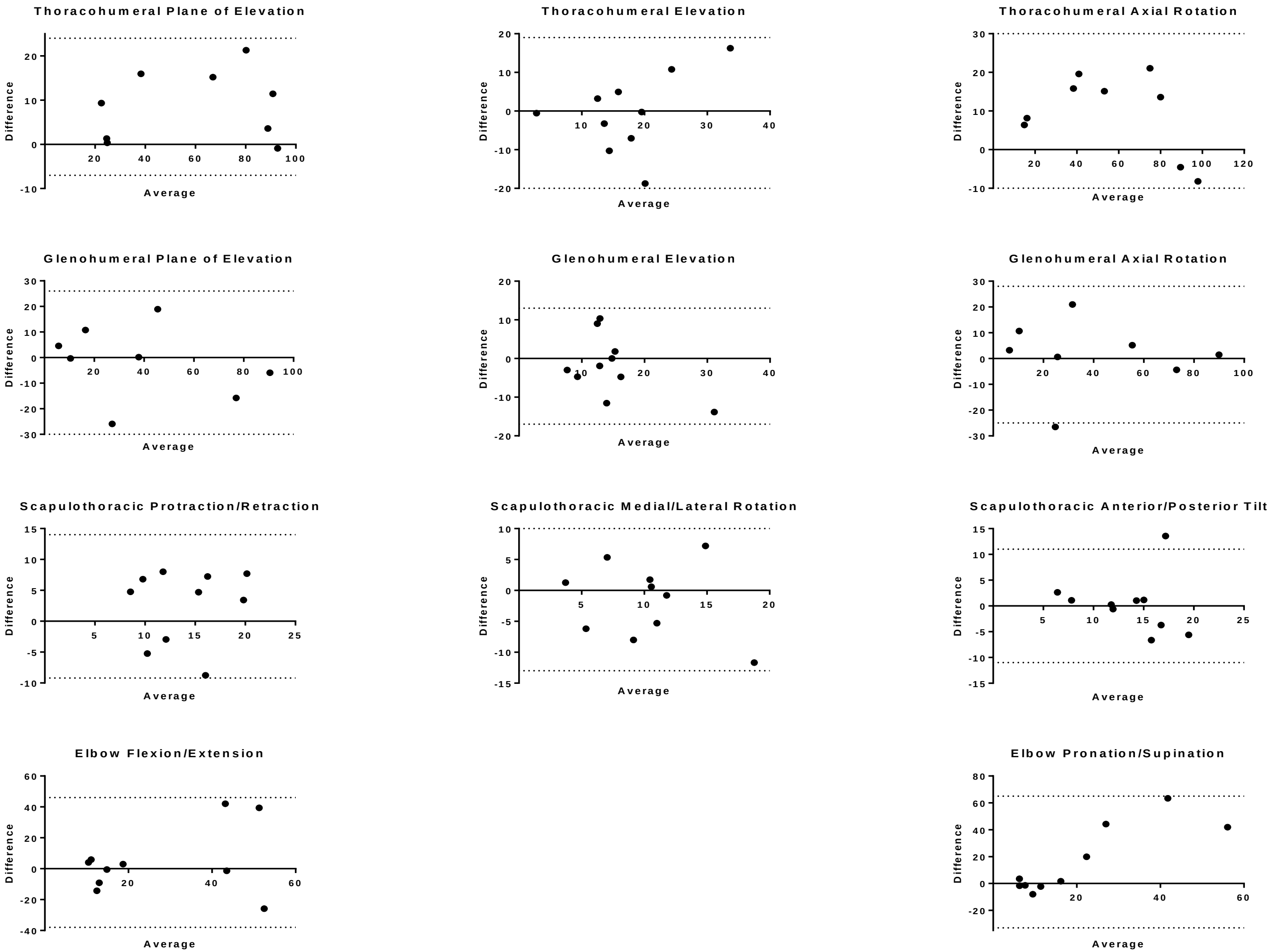


Figure 4.13: Bland and Altman plots for ROM in Hand-to-Spine Task

Units of measurement: Degrees; Mean of Measures ——— 95% Limits of Agreement (LOA) ············ Individual ●

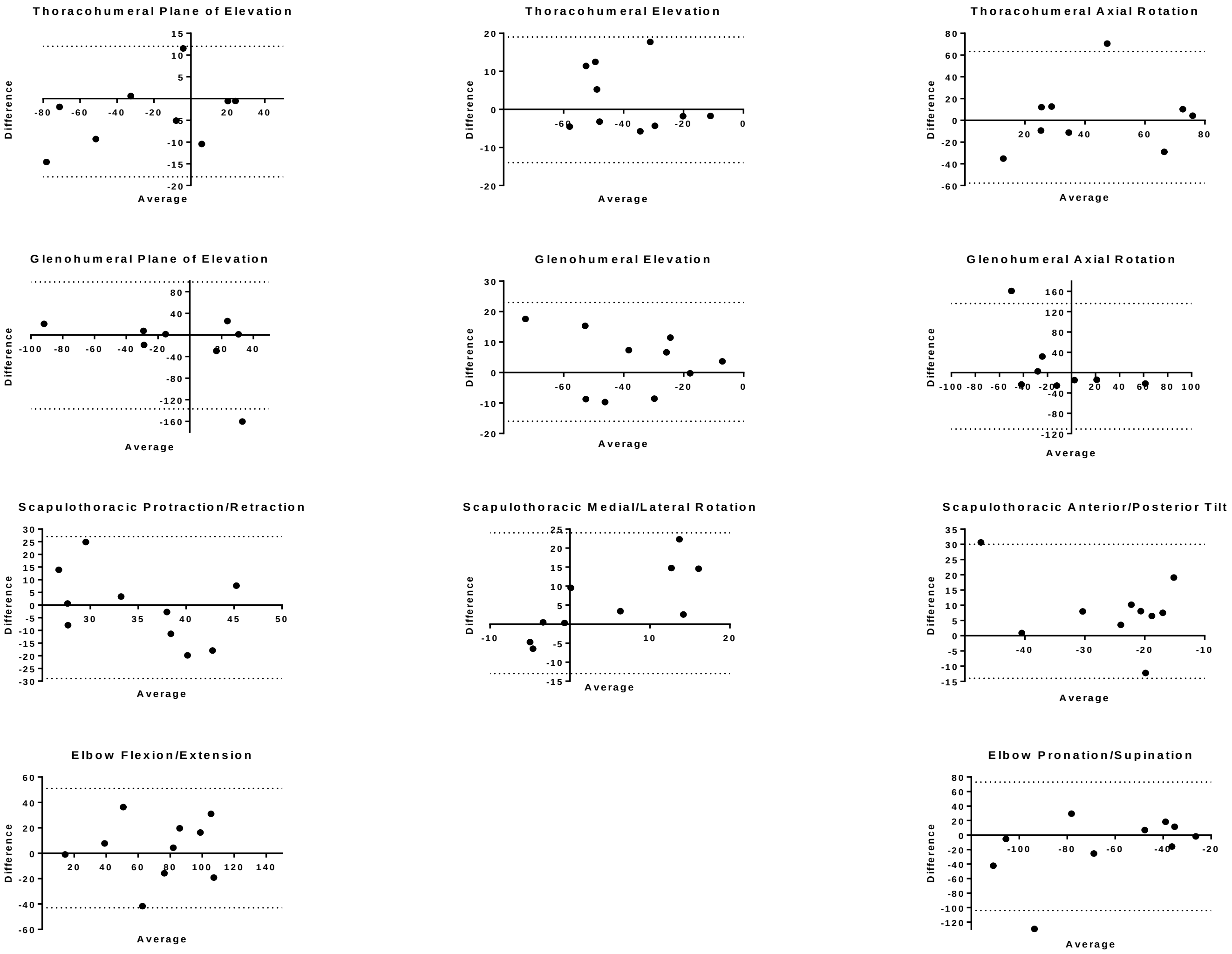


Figure 4.14: Bland and Altman plots for point of task achievement for Hand-to-Spine Task

Units of measurement: Degrees; Mean of Measures ——— *95% Limits of Agreement (LOA)* ·············· *Individual* ●

Table 4.10: Test-retest reliability of kinematic and spatiotemporal parameters for Hand-to-Spine Task

Units of measurement: Joint range of motion (ROM) and point of task achievement: Degrees; Duration: Seconds; SD: Standard Deviation; SEM: Standard Error of Measurement; MDC: Minimal Detectable Change; ICC: Intraclass Correlation Coefficient; 95%CI: 95% Confidence Intervals; 95% LOA: 95% Limits of Agreement; *: non-normally distributed data (median and interquartile range reported); ": negative ICC recorded; +: negative Cronbach's Alpha (ICC/SEM/MDC not calculated)

Kinematic Parameters	Mean(SD)	SEM Degrees	MDC	ICC	ICC 95% CI	Mean Difference	SD Difference	95% LOA
Thoracohumeral Joint								
ROM Plane of Elevation	58.9(31)	**8**	22	**0.93**	0.76→0.99	8.6	7.9	-7.0→24
ROM Elevation	17.5(9)	**5.9**	16.3	**0.47**	-0.15→0.84	-.49	10	-20→19
ROM Axial Rotation	56.2(30.9)	**9.4**	26.1	**0.91**	0.67→0.98	9.7	10	-10→30
PTA Plane of elevation	-21.8(38.3)	**5.6**	15.4	**0.98**	0.92→0.99	-3.4	7.7	-18→12
PTA Elevation	-38.3(15.4)	**5.8**	16	**0.86**	0.56→0.96	2.6	8.5	-14→19
PTA Axial Rotation	-13.3(23.3)	**17.5**	48.5	**0.43**	-0.24→0.83	2.8	30.9	-57.7→63.2
Glenohumeral Joint								
ROM Plane of Elevation	38.8(31)	**9.3**	25.8	**0.91**	0.65→0.98	-1.7	14	-30→26
ROM Elevation	14.7(6.4)	**4.6**	12.7	**0.48**	-0.15→0.84	-1.9	7.7	-17→13
ROM Axial Rotation	39.7(30.1)	**8.9**	24.6	**0.91**	0.66→0.98	1.4	14	-25→28
PTA Plane of elevation	-7.6(42.7)	**34.4**	95.4	**0.35**	-0.37→0.82	-19	60	-137→98
PTA Elevation	-36.8(19.6)	**7**	19.3	**0.59**	0.59→0.97	3.5	10	-16→23
PTA Axial Rotation	8.9(36.6)	**32.8**	91	**0.51**	-0.51→0.76	12	63	-111→136
Scapulothoracic Joint								
ROM Protraction/Retraction	14(4.1)	**3.5**	9.8	**0.23**	-0.97→0.75	2.6	6.0	-9.2→14
ROM Medial/Lateral Rotation	10.3(4.4)	**3.5**	9.7	**0.38**	-0.26→0.80	-1.6	6.0	-13→10
ROM Anterior/Posterior Tilt	13.6(4.2)	**3.2**	8.8	**0.42**	-0.22→0.81	.32	5.6	-111→11
PTA Protraction/Retraction	34.9(6.8)	**"**	"	**"**	"	-.93	14	-29→27
PTA Medial/Lateral Rotation	3.2(16.1)*	**6.3**	17.6	**0.46**	-0.17→0.83	5.7	9.3	-13→24
PTA Anterior/Posterior Tilt	-25.6(10.6)	**8**	22.2	**0.43**	-0.20→0.82	8.2	11	-14→30
Elbow Joint								
ROM Flexion/Extension	27.1(18)	**12.8**	35.3	**0.5**	0.12→0.85	4.3	21	-38→46
ROM Pronation/Supination	20.5(16.9)	**15.4**	42.8	**0.16**	-0.46→0.69	16	25	-33→65
PTA Flexion/Extension	79.1(42)*	**15.3**	42.5	**0.75**	0.29→0.93	3.8	24	-43→51
PTA Pronation/Supination	-64.1(31.5)*	**26.1**	72.5	**0.31**	-0.33→0.77	-15	45	-104→73
Duration of Task(Seconds)	1.18(0.52)*	**0.23**	0.65	**0.58**	0.0→0.88	-0.12	0.37	-0.85→0.61

4.5 Spatiotemporal parameters

Task duration is presented in the individual tables for each task (Tables 4.5-4.10). Examination of the B&A plots demonstrated that the External Rotation Task showed a bias for shorter duration at time 2 in all but one participant suggesting a possible learning effect for this task (Figure 4.15). Both the Abduction and Hand-to-Mouth Task had the smallest differences between times with two outliers widening LOA. Only the Abduction Task had acceptable reliability with an ICC of 0.93; SEM 0.14 seconds. For all other tasks ICC ranged from 0.32 to 0.56 and SEM from 0.02 seconds to 6. 2 seconds. These results suggested poor reliability for spatiotemporal parameters of task performance in children with OBPP.

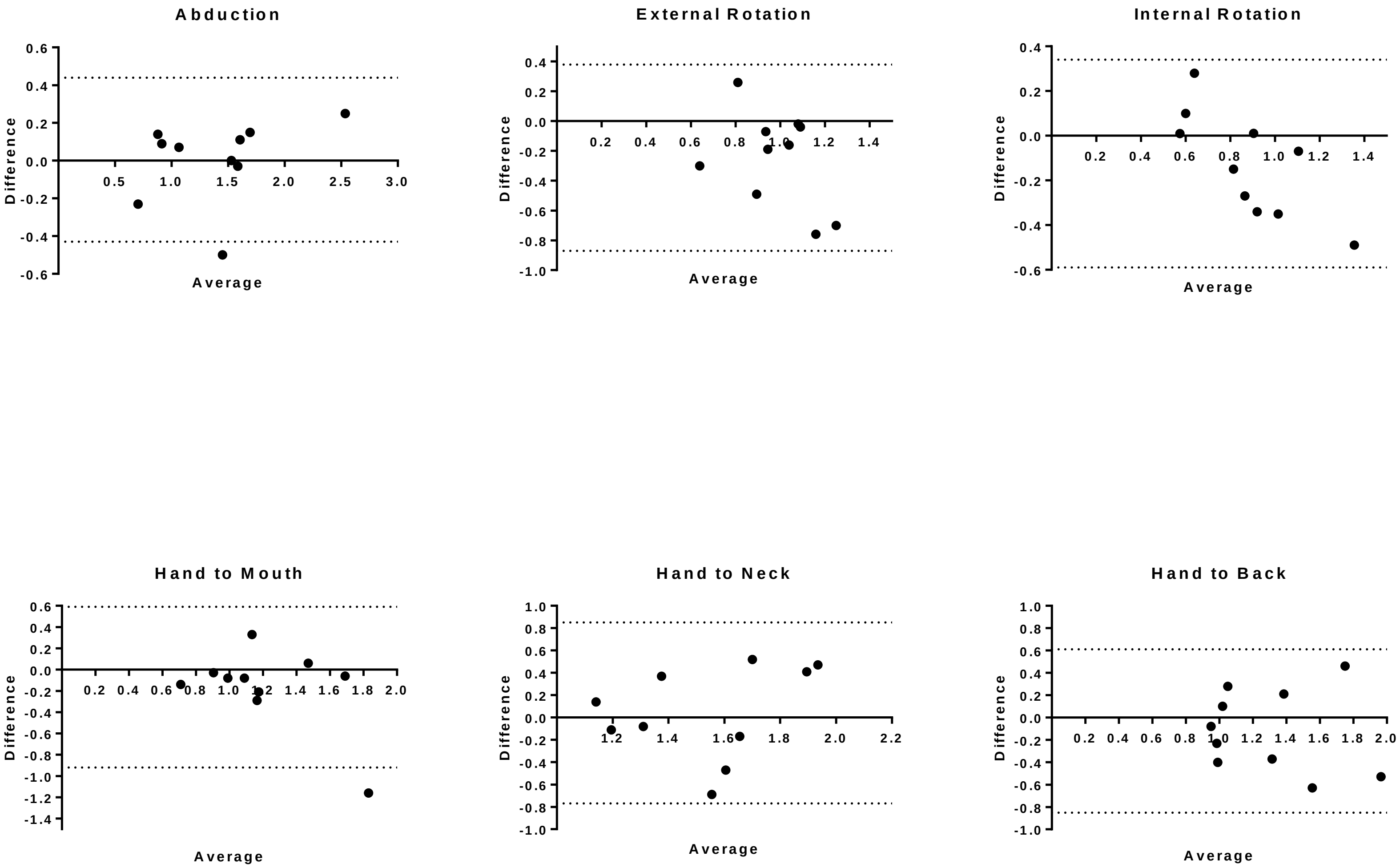


Figure 4.15: Bland and Altman Plots for Duration of Tasks

Units of measurement: Seconds; Mean of Measures 95% Limits of Agreement (LOA) Individual

4.6 Summary

For the majority of variables neither the reliability coefficient ICC nor SEM reached acceptable limits (Table 4.11). The Abduction Task had the most acceptable reliability measures with 10/18 variables achieving acceptable ICC and SEM levels. Except for the ST joint the Hand-to-Spine Task demonstrated reasonable reliability in the TH/GH joints though this differed for both variables of ROM and PTA. The External Rotation Task had the lowest acceptable reliability measures with 2/18 reliable variables recorded. For both ROM and PTA conflicting results were obtained for most variables with 4/18 achieving reliability in both. TH and GH elevation at PTA had reasonably consistent reliability across all tasks. TH and GH AR did not have acceptable reliability for PTA in any task. ST P/R and elbow P/S were not reliable for any task examined. The possible explanations for these findings are discussed within the context of current literature in the following sections.

Table 4.11: Test-retest reliable kinematic variables of the upper limb as measured by this three dimensional upper limb model in children with obstetric brachial plexus palsy

Intra Class Correlation (Standard Error of Measurement in degrees); POE: Plane of elevation; E: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral rotation; A/P: Anterior/Posterior Tilt; F/E: Flexion/Extension; P/S: Pronation/Supination; NR: Not Reported

	Thoracohumeral			**Glenohumeral**			**Scapulothoracic**			**Elbow**	
	POE	**E**	**AR**	**POE**	**E**	**AR**	**P/R**	**M/L**	**A/P**	**F/E**	**P/S**
Abduction											
ROM	0.82(7.8)	0.98(4.7)	0.81(10.3)	-	0.81(8.1)	0.83(9.9)	-	0.79(7.7)	0.95(3.5)	NR	NR
PTA	-	0.97(6.3)	-	-	-	-	-	0.81(6.5)	0.95(6.1)	NR	NR
External Rotation										NR	NR
ROM	-	-	-	-	-	-	-	-	-	NR	NR
PTA	-	-	-	-	0.77(10.4)	-	-	0.75(6.2)	-	NR	NR
Internal Rotation										NR	NR
ROM	-	-	-	-	-	0.86(7.1)	-	-	-	NR	NR
PTA	0.96(8.8)	0.77(4.9)	-	0.96(8.7)	0.92(6.5)	-	-	-	-	NR	NR
Hand-to-Mouth											
ROM	-	-	-	-	-	-	-	0.79(3.3)	-	0.77(8.3)	-
PTA	0.91(3.9)	0.88(7.2)	-	0.88(6.2)	0.87(9.4)	-	-	-	0.77(7.5)	-	-
Hand-to-Neck											
ROM	-	-	0.81(9.1)	-	-	-	-	-	-	-	-
PTA	-	0.90(9.2)	-	-	0.90(8.4)	-	-	-	0.86(9.9)	-	-
Hand-to-Spine											
ROM	0.93(8)	-	0.91(9.4)	0.91(9.3)	-	0.91(8.9)	-	-	-	-	-
PTA	0.98(5.6)	0.86(5.6)	-	-	-	-	-	-	-	-	-

4.7 Discussion

It is crucial that clinicians use objective outcome measures to inform management strategies, evaluate change over time or after an intervention. As already explored in Chapter 1 Introduction and Literature Review, 3D-ULMA has the potential to provide an objective outcome measure to evaluate upper limb kinematic patterns. It is essential to assess the psychometric properties of an outcome measure prior to its implementation in clinical practice. Despite acknowledged limitations, the AM was identified as the best available method of tracking dynamic scapular motion (Lempereur et al., 2014). Assessment of test-retest reliability is necessary to guide its potential clinical implementation. To the best of our knowledge, this is the first research study to determine test-retest reliability and measurement errors of 3D-ULMA using the AM in children with OBPP. This section discusses the reliability results in the context of existing literature and implications for its implementation in clinical practice.

4.7.1 Experience of the assessor with sample population

Due to the altered anatomical development and shoulder girdle alignment in children with OBPP it is important that the assessor is experienced with this population. Inter-observer reliability of a paediatric and generalist physiotherapist, using a 2D movement analysis system (V-scope) to quantify elbow and shoulder active movement in children with OBPP, has been examined (Bialocerkowski et al., 2006). Thirty children with OBPP, mean age 2 years 6 months (±1 year 2 months), were assessed by both assessors on two occasions one week apart. The paediatric physiotherapist was found to be more reliable in all movements except for shoulder flexion, ICC 0.29; SEM 7.8º compared with ICC 0.69; SEM 6.3º for the generalist physiotherapist. While this study did not analyse 3D motion, it highlighted higher errors in movement analysis when the assessor was not familiar with the specific population. In this research the single assessor had more than 10 years' clinical experience working with children with OBPP and two years' experience working in a motion analysis laboratory. This reduced the potential contribution of the assessor's variability to the reliability of this research.

4.7.2 Current reliability studies

While this is the first study to examine reliability of 3D-ULMA in children with OBPP, it has already been explored in TDC and children with HCP (Mackey et al., 2005, Fitoussi et al., 2006, Schneiberg et al., 2010, Butler et al., 2010, Reid et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Lempereur et al., 2012, Vanezis et al., 2015). There were several methodological differences between the literature that limit comparison both with each other and this research. Refer to Appendix 4.1 for detailed outline of the methodological differences between studies. Only Jaspers' research was sufficiently similar in methodology to permit direct comparison with the only differences being: population, task set analysed and lack of reporting of the GH joint.

4.7.2.1 Influencing factors on reliability identified in the literature

While the general consensus is that 3D-ULMA has acceptable reliability in TDC and children with HCP, critical analyses of these studies highlight certain cautions when interpreting results. Various factors were identified as influencing reliability. Some of these have a degree of adjustability while others were inherent to the challenges presented by the upper limb. These factors included: magnitude of ROM, the larger the ROM the more reliable the findings (Mackey et al., 2005, Reid et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Lempereur et al., 2012, Vanezis et al., 2015); POE, sagittal plane being more reliable than transverse or coronal in both intra and inter-session reliability (Mackey et al., 2005); intrinsic variability in task performance (Mackey et al., 2005, Jaspers et al., 2011b, Jaspers et al., 2011c, Lempereur et al., 2012, Vanezis et al., 2015); task complexity (Mackey et al., 2005); measurement errors i.e. marker placement/ inherent problems with rigid segmental modelling/calibration position/joint centre calculations/marker view; inadequate standardisation of start and static calibration positions (Butler et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). With regard to the last point, caution was advised against implementing increased standardised positions in certain populations due to both its impact on necessary compensations and difficulty achieving a repeatable standardised position in certain participants with severe impairment. The influences of the above factors on current results are considered in the following sections.

4.7.3 Reliability of 3D-ULMA in children with OBPP

The overall findings of this research suggest that 3D-ULMA using the AM has poor reliability in this population when used to assess the tasks of the modified Mallet scale. The results were very noisy with no task, joint or rotation axis achieving consistent reliability. The following sections discuss the findings of the reliability study in the context of acknowledged factors influencing reliability. It is important to note that while each factor is discussed individually several may have influenced a single reliability finding.

4.7.3.1 Influence of magnitude of ROM on reliability

Interpreting error within the context of the magnitude of total ROM achieved is very important. An error margin of 5º will obviously be less acceptable over a ROM of 10º compared with 60º. Absolute measures of error, such as SEM, provide a more intuitive interpretation of results than reliability coefficients in isolation (McGinley et al., 2009). They permit comparison with the actual units of measurement and are more clinically relevant.

It has been reported in the literature that joints with larger ROM often demonstrated higher reliability coefficients and lower relative error (Reid et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). While in general this was true for this research, with better reliability in the tasks that demanded larger ROM, it was not consistent. Contrasting findings were seen in the two tasks that recorded the largest magnitude of ROM in TH elevation. The Abduction Task demonstrated acceptable reliability of this variable (mean ROM 69º ±32.7º; ICC 0.98; SEM 4.7º). In contrast, the actual largest mean ROM achieved was during

TH elevation in the Hand-to-Neck Task and this did not have acceptable reliability (mean ROM 80º±13º; ICC 0.66; SEM 13.4º). In addition, despite the ST joint recording its largest ROM in all three axes during the Hand-to-Neck Task none achieved acceptable reliability (ICC 0.06-0.72). This contrasted with the Abduction Task where similar ROM was achieved in all three rotation axes but two (ST M/L rotation ICC 0.79; ST A/P tilt ICC 0.95) had acceptable reliability. The contrasting reliability of these variables, despite the larger ROM, demonstrated the varied challenges in assessing reliability of upper limb kinematics.

These observations may be a reflection of the chosen tasks. The lower reliability seen in the functional tasks may reflect the inherent variability of task performance. The Abduction Task is simpler and more defined in its performance while the Hand-to-Neck Task can be completed through a variety of movement combinations. This suggests that in this research study, task complexity was more influential on reliability of 3D-ULMA than magnitude of ROM achieved.

4.7.3.2 Influence of task complexity on reliability

As identified in the preceding section, task complexity presented significant challenges to reliable 3D-ULMA kinematic measurement. The lack of a cyclical nature in upper limb function complicates the assessment of reliability of a measurement tool as the inherent variability of task performance can result in unreliable findings. The motivation for this research was to enhance the clinical service provision for children with OBPP. In recognition of the importance of efficient functional ability, the tasks chosen for analysis were based on a valid and reliable clinical measure routinely used to assess functional performance in children with OBPP. The six tasks of the modified Mallet scale (Abzug et al., 2010) are divided into three gross movements and three functional tasks. No task demonstrated consistent reliability across all joints and rotation axes. This highlighted that no one task, from simple to complex, can provide reliable data on all joint kinematics of the upper limb in children with OBPP. The following paragraphs identify the salient points from the overall reliability of these tasks and where possible, compare with existing findings in the literature.

The Abduction Task was the simplest to measure as the main movement occurred in one plane, the scapular plane (TH POE 45º(±24º)). Analysis of planar movements has been found to be easier and more reliable than the more complex, combined movement patterns typical of upper limb function (Lempereur et al., 2012, Vanezis et al., 2015). The acceptable reliability of this task was similar to previous research where a comparable task, reach sideways, was analysed in TDC and children with HCP (Jaspers et al., 2011b, Jaspers et al., 2011c). These studies reported similarly high ICCs of >0.75 with SEMs of 3º to 9º in nearly all rotation axes with the exception of poor reliability in ST A/P tilt in children with HCP and ST M/L rotation in TDC.

No studies in the literature assessed tasks similar to the pure External and Internal Rotation Tasks examined in this study. The principal movement of these tasks should be in the plane of GH AR. While neither task is complex to perform per se, active rotation is a recognised challenge for all children with OBPP with a lack of external rotation a characteristic feature of all levels of the NC (Hale et al., 2010, Breton et al., 2012, Heise et al., 2015). The External Rotation Task was the least reliable task; two variables demonstrating acceptable reliability, GH elevation and ST M/L rotation at PTA. This may reflect compensatory strategies adopted in the absence of pure active GH external rotation. The Internal Rotation Task had somewhat better reliability in the TH/GH joints. Acceptable reliability was found in TH/GH POE/elevation at PTA and GH AR (ROM). No ST joint rotation axis achieved acceptable reliability limits in the Internal Rotation Task.

As both tasks were performed in the same session this suggests that the variable reliability cannot be solely due to replacement of the markers or axis definition error. It questions the ability of the model to reliably track the External Rotation Task. An alternative position than arm by the side, as used in the modified Mallet scale, may be appropriate as this position is associated with the mathematical problem of gimbal lock due to two axes being aligned in the same orientation (Rundquist et al., 2003, Šenk and Chèze, 2006, Jaspers et al., 2011c). Furthermore, the chosen reliability coefficient may have influenced results. As the ICC is dependent on the variation in task performance amongst participants, a lower ICC may have been generated due to the poor functional ability of participants during the External Rotation Task, in contrast with the better ability to complete the Internal Rotation Task during the sessions.

Of the three functional tasks, Hand-to-Neck had the poorest reliability. As previously discussed (Section 4.8.3.1) this task was the most complex. It is difficult to achieve in the presence of limited elevation and external rotation, both of which are limited in children with OBPP. No task was comparable in the existing literature. Different strategies were observed in the participants with OBPP as they attempted to complete the task, with frustration noted in some children. This may have influenced inherent reliability of task performance with different strategies being adopted to better achieve the task in each trial. The two other functional tasks, Hand-to-Spine and Hand-to-Mouth which are less complex, had better, but still varied levels of reliability with the TH/GH joints at PTA the most consistently reliable variables. Reliability of gross movements within functional tasks e.g. TH elevation, was greater than those less defined for task completion e.g. elbow supination, ST motion. This concurred with the conclusion by Vanezis et al. (2015) that the gross movement of TH elevation was more reliable than the more refined motions of elbow P/S in which higher errors were observed.

Elbow joint kinematic data were only evaluated in the functional tasks as it was considered crucial to their successful completion. Only one variable, elbow F/E (ROM) in the Hand-to-Mouth Task (ICC 0.77; SEM 8.3º) achieved acceptable reliability. Altered head and trunk positon in addition to variability in task performance may have influenced the degree of elbow F/E required. They are not reported in this research. Elbow P/S had consistently poor reliability in this study. Contrasting results were found for the Hand-to-Mouth Task in previous studies with acceptable reliability found for both rotation axes in TDC (Jaspers et al., 2011c) and for elbow F/E in children with HCP (Jaspers et al., 2011b). In this research, for the Hand-to-Spine and Hand-to-Neck Tasks marker view of forearm cluster was a problem which contributed to poor reliability. Increasing the number of cameras used is recommended for future studies to enhance marker visibility.

These findings highlighted the challenges in selecting appropriate tasks for examination both due to: limitations of the model in tracking planar and combined movements; the impact of the particular population's impairments on task performance. The modified Mallet scale was chosen as it is routinely used in clinical practice and the objective was to inform clinical management of this cohort. However, it was evident from these results that the poor reliability of the tasks negates the benefits of using a recognised clinical scale. Careful selection of tasks based on the clinical questions but recognising limitations of the model is crucial. Based on the results of this research the Abduction Task was the only one that achieved an acceptable level of reliability across all joints while the Internal Rotation, Hand-to-Mouth and Hand-to-Spine Tasks achieved acceptable reliability in at least two of the TH/GH joint rotation axes. Further work on the dynamic tracking of the upper limb during functional activities in this cohort is required prior to clinical application.

4.7.3.3 Influence of rotation axis on reliability

Due to the large number of degrees of freedom available and the anatomical alignment of the upper limb, producing a biomechanical model that reliably measures all rotation axes has proved difficult (de Groot, 1997, Lempereur et al., 2014). Computerised 3D gait analysis is currently the “reference standard” for analysing gait patterns. However even for 3D gait analysis, variable reliability has been reported for the different movement planes with the transverse plane being the least reliable (Eve et al., 2006, Meldrum et al., 2014). The findings of this research demonstrated that with the exception of consistently poor reliability of ST P/R and elbow P/S each axis demonstrated variable reliability across all joints and tasks. This further highlighted the complexity of defining the upper limb and the difficulty in analysing its movements using 3D-ULMA.

GH and TH elevation at PTA were reliable in all but one task each; Abduction and External Rotation respectively. This was a positive finding as elevation is compromised in children with OBPP meaning that 3D-ULMA could reliably evaluate this kinematic parameter. This also concurred with previous research where elevation was the most reliable rotation axis (Mackey et al., 2005, Jaspers et al., 2011b, Jaspers et al., 2011c). However, this was not consistently observed in the ST joint. ST M/L rotation demonstrated acceptable reliability in the Abduction Task for both PTA and ROM, in the External Rotation Task at PTA and Hand-to-Mouth Task for ROM. This finding suggests limited ability of the AM to reliably track ST kinematics in this plane.

As mentioned above ST P/R had poor reliability in all tasks analysed in this research. This was similar to findings of previous studies looking at TDC (Jaspers et al., 2011c) but contrasted with findings in children with HCP (Jaspers et al., 2011b) where ST P/R had acceptable reliability in all comparable tasks (reaching sideways; hand to mouth; hand to head). This was possibly due to the pathological differences in the population groups. The biomechanical alignment of the scapula in children with OBPP is quite altered compared with TDC and children with HCP (Nath et al., 2007) which may compromise the model's ability to accurately track movement. Therefore, caution is advised when interpreting results of ST P/R with respect to describing characteristic kinematic patterns in children with OBPP.

In this research, POE and AR had similar inconsistency in terms of reliability, both achieving acceptable reliability in 10/24 potential variables which was <50%. This is possibly a reflection of the difficulty in tracking the movements accurately both within available degrees of freedom and movement combinations. It was acknowledged in the literature that crosstalk and gimbal lock were a problem in 3D-ULMA (de Groot, 1997, Šenk and Chèze, 2006). These were more common in certain planes and arm positions contributing to inaccurate kinematic recordings. Previous research studies have demonstrated that TH/GH AR had the highest measurement errors (Butler et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). It was interesting to note that despite poor overall reliability of this axis six TH/GH AR variables for ROM had acceptable reliability. One of these was during the Internal Rotation Task (GH AR: ICC 0.86; SEM 7.1º). This acceptable reliability is useful for further analysis of characteristic kinematic differences between TDC and children with OBPP as an increased posture of internal rotation has been observed clinically. TH and GH POE were reported to have high errors at start and end points of tasks further suggesting difficulty standardising a reference position for this plane (Vanezis et al., 2015). Furthermore, frontal and transverse planes had lower intra-session reliability during the performance of functional tasks suggesting variation in task performance particularly in these planes (Mackey et al., 2005). In conclusion, this research's findings concurred with existing literature that reliability varies with rotation axis.

The elbow joint was only analysed in three tasks as it was considered essential to their effective completion. In contrast to other studies elbow P/S had poor reliability in all three functional tasks while elbow F/E demonstrated acceptable reliability in one of three tasks. To demonstrate the challenges presented at the same joint across different rotation axes a sample of elbow joint motion is presented from the oldest and youngest participants during the Hand-to-Mouth Task (Figures 4.16 and 4.17). Both the mathematical problem of gimbal lock (Figure 4.17 A) and variability in ability to track elbow P/S were observed (Figure 4.16 A). In contrast elbow F/E was reasonably consistent across the two participants and trials. This highlighted the impact the rotation axis had on reliability within the same participant.

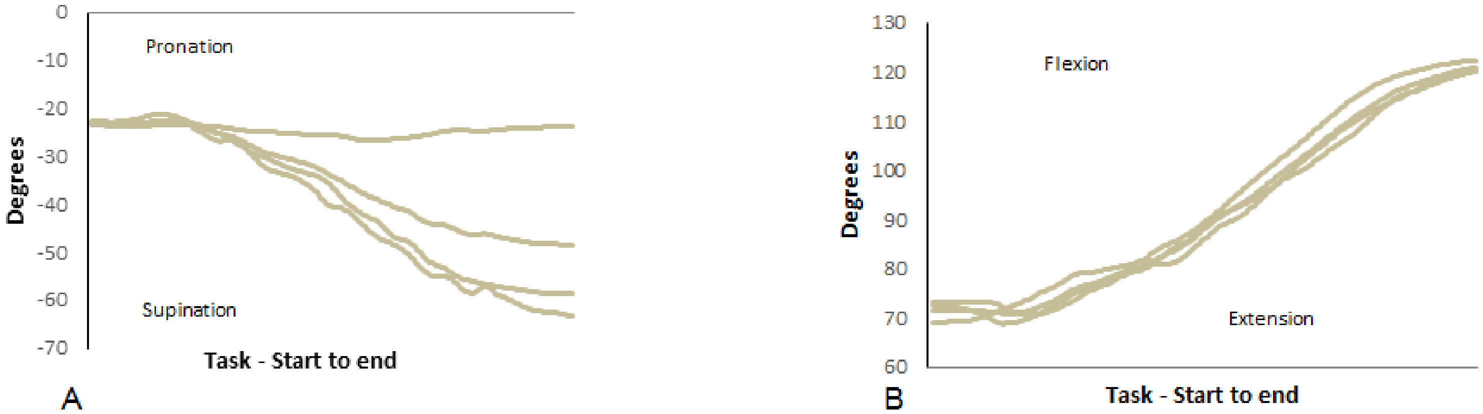


Figure 4.16: Hand-to-Mouth Task in the oldest participant with OBPP showing A - elbow pronation/supination; B - elbow flexion/extension

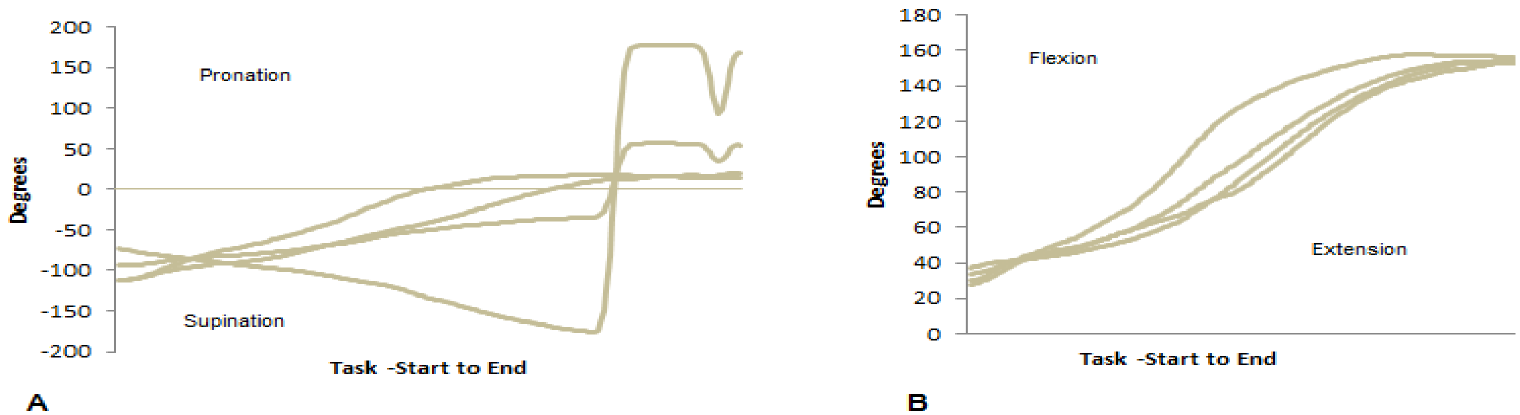


Figure 4.17: Hand-to-Mouth Task in the youngest participant with OBPP showing A - elbow pronation/supination; B - elbow flexion/extension

As with 3D gait analysis, the ability to reliably track movement across all rotation axes was not consistent. Acceptable reliability in TH/GH elevation was demonstrated across the majority of tasks. While TH/GH POE and AR had poorer reliability, this concurred with existing literature. As scapular dyskinesis is an acknowledged kinematic feature of children with OBPP (Duff et al., 2007, Russo et al., 2014) the AM was chosen as the most valid method of dynamic scapular tracking (Lempereur et al., 2014). However, these results indicated that the AM does not consistently reliably measure ST motion in any axis (Table 4.10). The following sections analyse in more detail the various methodological errors contributing to reliability of 3D-ULMA in children with OBPP.

4.7.3.4 Influence of methodological errors on reliability

It is not possible to completely avoid methodological errors when using measurement tools. Recognition of that fact places the onus on the user to control for errors as much as possible. Various methodological errors in 3D-ULMA have been recognised in the literature (Butler et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). Their contributions to the poor reliability of the 3D-ULMA model used in this research are outlined in the following paragraphs.

4.7.3.4.1 Anatomical coordinate system definition

Firstly, definition of the anatomical coordinate system (ACS) which describes the angular position of axes, planes and rigid bodies, may have influenced reliability of the model. ACS definition is dependent on identification of bony landmarks through palpation, placement of technical clusters, reliability of pointer acquisition and postural alignment of the upper limb during a static calibration. Altered biomechanical alignment of children with OBPP, especially of the shoulder complex (Nath et al., 2007, Hale et al., 2010), made accurate palpation of bony landmarks more challenging. Furthermore, due to the inherent variability and age of participants consistent implementation of the standardised position for static calibration proved difficult.

Slight variation in definition of ACS influences axis definitions. This has been examined in the lower limb (Brennan et al., 2011) but exploration of its influence on upper limb kinematics is limited. It has been found that definition of the ST P/R axis was dependent on repositioning of the AC while ST M/L rotation and A/P tilt were less sensitive (van Andel et al., 2009). The ST P/R axis was the most difficult to measure reliably using the AM in children with OBPP suggesting that replacement of either the scapular markers or the cluster itself were subject to variation. The meeting point between the acromion and the scapular spine has been identified as the most accurate location for the AC (Shaheen et al., 2011). While this position was found to be least affected by skin deformation, replacement error was not assessed meaning the ability to reliably replicate this position has not been determined. Caution has already been advised when interpreting the scapular segment due to sensitivity to marker placement. This was identified by the difference seen between intra and inter-session errors (van Andel et al., 2009, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). Therefore, it was decided to use the position of the acromial angle for placement of the AC as it has been used in a paediatric population of TDC and children with HCP with its repeatability examined (Jaspers et al., 2011b, Jaspers et al., 2011c). Should the meeting point of the acromion and scapular spine be determined repeatable then its use in future studies may improve reliability of the AC, thereby improving reliability of ST axis definition.

SC with the arm in a position of rest, palm down on ipsilateral knee was used in this study. A recent study, albeit on adult cadaver subjects, found greater errors in scapular orientation when only SC was performed as opposed to DC (Cereatti et al., 2015). DC decreased error to -1.0º to 14.2º from an error of 6.2º to 44º in SC. DC at rest position and at a second angle close to end range was concluded to allow for greater compensation of soft tissue artefact than SC in adults (Brochard et al., 2011). However, reliability of DC while still within acceptable limits was less than SC. Therefore, DC was not adopted for this study based on the rationale that due to varied abilities in children with OBPP a standardised second calibration position would be difficult to determine prospectively. For future research, performing a second calibration at either 60º GH joint abduction or, as close as possible, may improve reliability (Shaheen et al., 2011). To our knowledge, the impact of marker placement and palpation on other joints has not been reported in the literature but it is reasonable to assume that inaccurate palpation and marker placement would affect reliability of the model. This needs to be further examined in the literature to accurately inform interpretation of 3D-ULMA model's findings.

4.7.3.4.2 Gimbal lock

Secondly, the well-recognised mathematical problem of gimbal lock and its presence in this research has been discussed (Chapter 3 Methods: Section 3.7.2.1). While it is recommended that rotation sequences used in the calculation of joint kinematics should avoid singular positions (e.g. 180º elevation) no one rotation sequence allows for this in the GH joint (Šenk and Chèze, 2006). Gimbal lock may have contributed to the overall poor reliability seen in both the Internal and External Rotation Tasks. Both were performed close to one of the identified gimbal lock positions i.e. 0º of arm elevation (Anglin and Wyss, 2000, Šenk and Chèze, 2006, Phadke et al., 2011). When the humerus is parallel to the trunk POE cannot be distinguished from AR leading to illogical angles being determined by the mathematical model (Phadke et al., 2011). The start position of hand on ipsilateral knee, similar to that used by Jaspers et al. (2011b) and Jaspers et al. (2011c), was adopted to ensure a degree of shoulder elevation at all times. From the graphs it can be seen that the lowest degree of elevation was ~5º with the majority of children with OBPP being elevated about 20º at start and end of these tasks (Chapter 5 Kinematic Results: Section 5.4, Figure 5.3 and Section 5.5, Figure 5.4). This is close to the recommended 30º of elevation recommended by Šenk and Chèze (2006) as a good starting point to avoid gimbal lock when using the ISB recommended sequence of rotation (YXY). The incidence of gimbal lock was not very high for these tasks (Appendix 3.7) suggesting that other factors, as discussed in the preceding sections, contributed to their poor reliability. The poor reliability of the ST joint in the Hand-to-Spine Task may be a consequence of the chosen rotation sequence as recommended by the ISB (Wu et al., 2005) as it was not found to be the best sequence for backward elevation of the GH joint (Šenk and Chèze, 2006).

4.7.3.4.3 Marker view

Thirdly, marker view was a challenge during the performance of some tasks. This is likely to have contributed to poor reliability due to critical loss of view at certain points. There are two main reasons for this problem. The orientation of arm segments for certain movements compromised marker view e.g. forearm cluster during the Hand-to-Spine Task due to poor active supination and internal rotation posture of the arm or anterior trunk markers in the Hand-to-Mouth/Abduction Tasks. In addition, the motion analysis system used could only support four cameras. It is evident from the findings of this research that this is insufficient to capture all potential orientations of the upper limb throughout all tasks. This has not been identified as a significant problem in the literature, however most systems used more cameras (6-12) than were available for this research (Mackey et al., 2005, Fitoussi et al., 2009, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). Increasing the number of cameras may improve reliability of the current model in particular for the tasks identified above.

4.7.3.4.4 Standardised positions for task performance

Fourthly, direction was provided to standardise both start position and task performance through a consistent resting posture, verbal instruction and task demonstration. This reduces the amount of intrinsic variability within the measurement. Yet the difficulty in adopting standardised positions due to inherent variability of the upper limb, participant age and the desire to permit compensatory strategies, if required, rendered achieving consistency more challenging. This may have resulted in larger error due to both intrinsic variability and extrinsic error and highlights the difficulties in measuring functional task performance.

Goniometry is the most objective measure of upper limb passive and active ROM in children with OBPP used in clinical practice (Chang et al., 2013). While its reliability has not been specifically explored in this population both inter-session and inter-observer reliability has been explored in children (Riddle et al., 1987, de Winter et al., 2004, Wilk et al., 2009, Kolber et al., 2012). Assessment with goniometry is systematic with standard start positions, alignment of the upper limb segments, the goniometer itself and performance of the movement, both active and passive. This means that these reliability results are not comparable to goniometry. However, by combining the information gained from both assessments, actual available ROM through goniometry and kinematic patterns via 3D-ULMA, an improved understanding of upper limb function can be achieved.

4.7.3.4.5 Sample size

Finally, sample size may have impacted on reliability results especially of joints and tasks that only required small movements for successful completion. The sample size was calculated based on detecting a difference in External Rotation ROM. This ROM is larger than the average excursions of the ST joint which may have impacted on the reliability findings of this joint in particular. A larger sample size of each of the NC is recommended for future research.

In summary, various methodological errors had an impact on the reliability findings of this research. The degree of each is difficult to quantify. The influence of intra-session reliability was not statistically explored therefore its contribution to the reliability findings cannot be quantified. The main issues identified were palpation error especially for the scapula, definition of ACS, difficulty for model to track specific tasks or rotation axes, marker view and finally sample size may be too small for certain rotation axes due to naturally smaller movement ROM.

4.7.3.5 Reliability of ROM compared with PTA

To our knowledge, reliability of ROM achieved during task performance has not been reported in the literature. Passive and active ROM has been used clinically to assess effectiveness of interventions in children with OBPP (Chang et al., 2013). Therefore, it was appropriate that reliability of this variable be evaluated in 3D-ULMA in this population to identify if it has potential as an outcome measure.

In this research, magnitude of ROM was calculated by subtracting maximum from minimum to capture the full amplitude of movement for each task (van Andel et al., 2008, Petuskey et al., 2007). With the exception of the Abduction Task reliability of this variable was much less than PTA, a variable that has been investigated previously in the literature. Slightly different kinematic paths may have been taken to achieve the task each time. Intrinsic variability is an important element to be acknowledged and managed when examining reliability of a measurement (Schwartz et al., 2004). While not statistically analysed intrinsic variability of participants was observed in this research. Potential influencing factors were task demands with gross movements less varied than fine movements (Section 4.8.3.3) and age; older participants being less variable (Figures 4.18 and 19). The youngest participant demonstrated very little elevation in this task but even within that more variation was seen across each trial (Figure 4.18). The lack of elevation suggested either a failure of the model to accurately track movement or very limited shoulder ROM used in this task. This second scenario was possible in the more affected children. The pattern of movement of the oldest child with OBPP was more established and consistent across the two time points (Figure 4.19). Despite a slightly different start and end point the pattern was similar between the two sessions.

Inherent variability is an acknowledged difficulty with analysis of the upper limb. In light of this, and the poorer reliability of the variable ROM found in this research, PTA was considered a more reliable variable as regardless of the path travelled the end point should be more consistent.

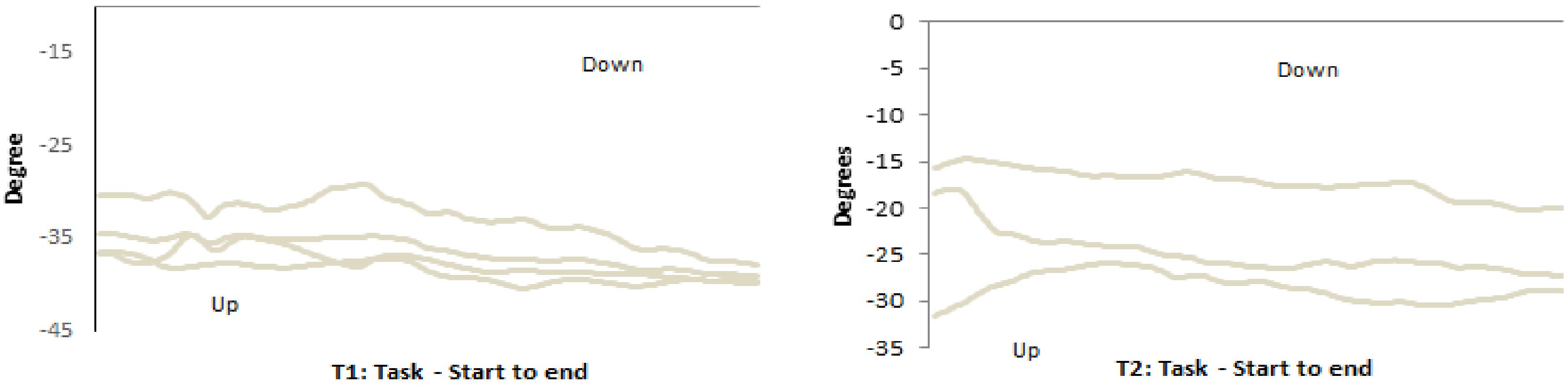


Figure 4.18: Hand-to-Mouth Task: Glenohumeral elevation for youngest participant with obstetric brachial plexus palsy (7 years 7 months)

T1 – Time 1; T2 Time 2

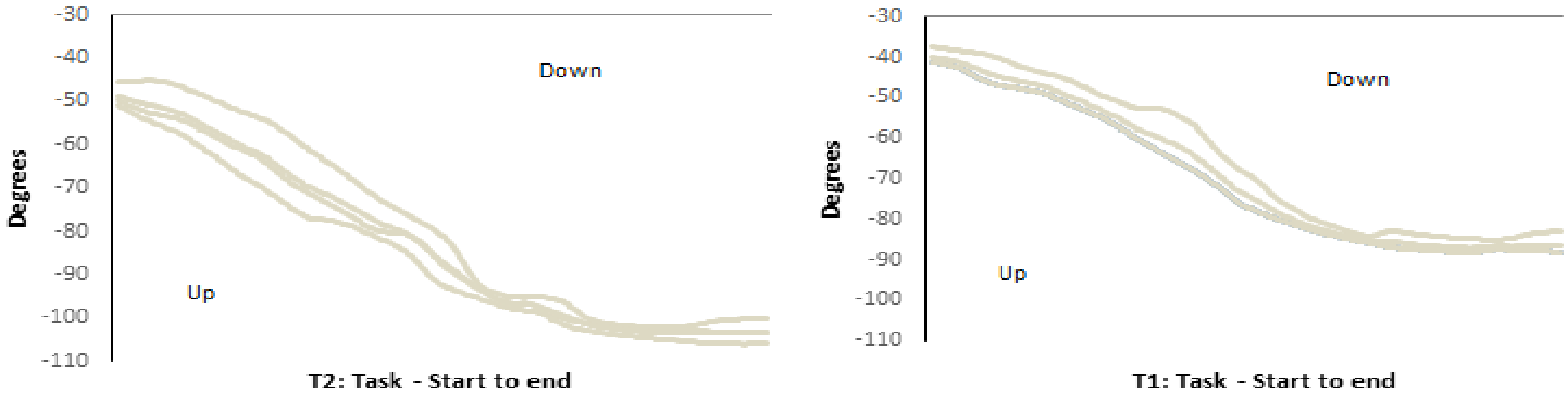


Figure 4.19: Hand-to-Mouth Task: Glenohumeral elevation for oldest participant with obstetric brachial plexus palsy (15 years 6 months)

T1 - Time 1; T2 - Time 2

Altered start points may have contributed to reduced reliability of ROM as this would impact on the ultimate ROM achieved but not necessarily on the end point. While efforts were made to ensure that the start point was as standardised as possible it has been acknowledged in the literature that certain planes, AR and POE, were difficult to accurately reference (Vanezis et al., 2015). While not statistically explored it was obvious from inspection of the kinematic graphs (Chapter 5 Kinematic Results: Figures 5.2-5.7) that greater variability was evident amongst the children with OBPP with regard to start point.

The influence of actual magnitude of ROM was discussed in Section 4.8.3.1 with the tasks that demanded greater ROM demonstrating more acceptable reliability. This was evident in the Hand-to-Spine Task where acceptable reliability was reported for ROM in TH/GH POE and AR while TH/GH elevation had poor reliability. This potentially reflected the small ROM required in TH/GH elevation for this task. However, it was interesting to note that both TH/GH elevation for PTA were reliable (ICC >0.86; SEM <7º). This suggested that while the ROM used in this rotation axis to achieve the task was unreliable, the ultimate degree of elevation at PTA was more consistent.

To the best of our knowledge this was the first research to examine reliability of dynamic ROM using 3D-ULMA in children with OBPP while performing functional tasks. PTA was found to be more reliable with the exception of the Abduction Task where 7/9 variables recorded acceptable reliability in ROM. Therefore, it can be concluded that while reliability of PTA can be improved, this variable is currently more appropriate to use as an outcome measure in 3D-ULMA of dynamic movement than ROM.

4.7.3.6 Spatiotemporal parameters

The hypothesis was proposed that children with OBPP would perform movements faster than TDC, using momentum to compensate for reduced active control and power. To effectively evaluate this hypothesis, the reliability of task duration was analysed. The Abduction Task was the only task to achieve acceptable reliability. This was in contrast to all other studies where spatiotemporal parameters were found to be consistently reliable (Butler et al., 2010, Reid et al., 2010, Jaspers et al., 2011b, Jaspers et al., 2011c, Vanezis et al., 2015). This poor reliability limited the ability to compare differences in task duration.

4.7.4 Limitations

Certain limitations need to be acknowledged as they contribute to the findings of the reliability aspect of this research. These are outlined in the following section.

Firstly, the CRC laboratory uses four CODAs as the standard for gait analysis, but given the larger amplitude and greater degrees of freedom of functional upper limb movements, markers were found to go out of view of the cameras more easily than in gait analysis. Furthermore, to enhance marker view for the majority of tasks the participant was orientated out of synchrony with the laboratory's GCS. This resulted in repeated gimbal lock during thorax movement. Thorax motion was not analysed in this research which limited interpretation of kinematic patterns. Based on visual observation of task performance during the trials, all children exhibited excessive trunk movements. By using a thorax technical cluster positioned on the posterior aspect of the thorax instead of markers placed directly on bony landmarks, marker view issue could be improved. Subsequent to starting this research such a model was developed and validated in TDC, the CRC trunk model (Kiernan et al., 2014). This would need to be integrated into ODIN's software prior to its implementation in 3D-ULMA. Therefore, for future protocols increasing the number of cameras and using a technical trunk cluster may assist in improving marker view. However, it is important to point out that some marker view issues were due to the impairment of the population and no amount of cameras would solve the problem in certain tasks.

Secondly, while efforts were made to standardise start position the ability of children to repeatedly adopt the same posture was observed to be challenging. Greater standardisation of start and end point using a customised seating system or a reference tool in which to place the arm at the start of each movement may improve consistency. However, this would have to be within reason as too much restraint may influence compensatory strategies or be impossible for some children to achieve due to their existing impairments.

Finally, SC with arm by side rather than DC was used for definition of the ACS. The arguments for this decision were discussed in Chapter 2 Development of Methodology: Section 2.4.2.2.4.3. In summary, the main reason for SC was concern with regard to the ability of the more severely impaired children to achieve a consistent second calibration position of 90º of abduction. Future studies should examine the effect of DC on reliability of task performance in children with OBPP to address the possible impact of this limitation.

4.8 Conclusions

This chapter determined the test-retest reliability of a 3D-ULMA model, using the AM, to track dynamic performance of functional tasks in children with OBPP. Overall it was found to have inconsistent reliability. Despite this conclusion it is the first study to provide details of measurement error in this population. TH and GH joint elevation were the most reliable in describing shoulder movement. The ST joint had poor reliability with ST P/R consistently unreliable. Elbow P/S also had poor reliability. This study concluded that ROM had lower reliability than PTA in this population. With regard to specific task reliability, the Abduction and Hand-to-Spine Tasks were the most reliable. This information will inform the interpretation of differences in task performance between children with OBPP and TDC in the cross-sectional study.

Chapter 5 Kinematic and Spatiotemporal Characteristics of Upper Limb Function: Results and Discussion

5.1 Introduction

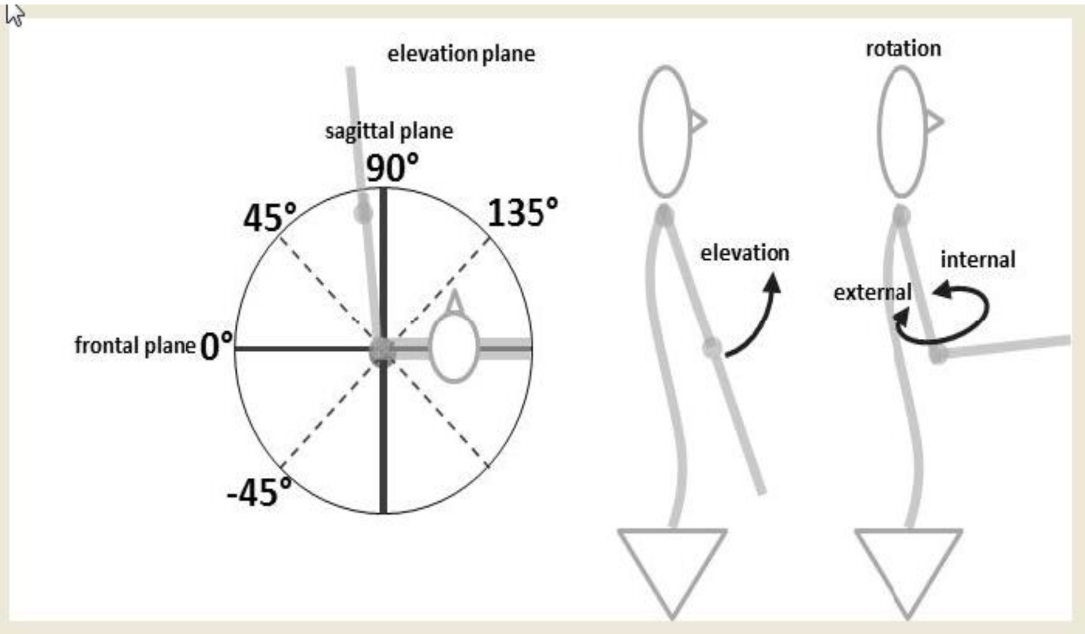
While similar patterns of movement were observed during task performance in both groups variation existed between individuals, with greater variation seen in children with OBPP. Overall the main features identified by this research concurred with existing clinical observations of increased postural internal rotation in all tasks; reduced GH joint motion and an altered scapular position of elevation and medial rotation. The following sections describe the kinematic findings of this research in more detail.

5.2 Descriptive statistics

Data were assessed for normal distribution and treated accordingly (Appendix 3.10). The mean and SD of TDC were calculated to produce a graph showing mean +/- 1SD for each joint and rotation axis of individual task to create a band of typical movement. The mean waveform of three trials for each participant with OBPP was then plotted against this band of typical movement. These are presented in Figures 5.2-5.7. Discrete kinematics, PTA and ROM, for TDC and children with OBPP and the statistical comparison between both groups are presented individually for each task in Tables 5.2-5.7.

5.2.1 Method used to describe shoulder movement

Prior to describing the kinematic findings during each task examined, the reader is reminded of the methods used to describe shoulder motion. The commonly used method of clinical examination recommended by the American Orthopaedic Society (1965) is insufficient when describing shoulder motion during the performance of daily functional tasks. Functional movements do not occur purely in the predefined planes of sagittal (forward flexion), frontal (abduction) or transverse (rotation). Therefore, this method inadequately describes shoulder motion during functional task performance. As this research examined functional task performance, the “globe system” was chosen as the most appropriate method for unambiguously describing all positions of the humerus in relation to the thorax and scapula (Figure 5.1) (Pearl et al., 1992, Doorenbosch et al., 2003).



Adapted from Doorenbosch et al. (2003)

Figure 5.1: Globe system of angle definition

Using this system, the TH and GH angles were described based on the orientation of the arm in the order of POE, elevation and AR. In this definition, 0¯POE represents the frontal plane or abduction, 90¯POE is equal to the sagittal plane or forward flexion. The scapular plane lies at ~30-40º anterior to the frontal plane and functional movements predominantly occur in this plane (Kolber et al., 2012, Giphart et al., 2013).

5.2.2 Results of spatiotemporal parameters

TDC took slightly longer than children with OBPP to perform each task, with duration ranging from 0.92 seconds to 1.57 seconds in TDC and 0.78 seconds to 1.56 seconds in children with OBPP. However, no significant difference was found between the two groups (Table 5.1). The Hand-to-Spine Task was the only task that approached a significant difference (p = 0.05).

Table 5.1: Differences between duration of task performance in children with obstetric brachial plexus palsy and typically developing children

Unit of measurement: Seconds; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; IQR: Inter quartile range

Task	TDC		OBPP		Difference	p-value
	Median	IQR	Median	IQR		
Abduction	1.45	0.84	1.20	0.59	-0.25	0.251
External Rotation	1.02	0.46	0.90	0.2	-0.03	0.349
Internal Rotation	0.92	0.48	0.78	0.22	-0.14	0.251
Hand-to-Mouth	1.08	0.67	1.05	0.48	-0.03	0.387
Hand-to-Neck	1.57	0.37	1.56	0.59	-0.01	0.654
Hand-to-Spine	1.47	0.78	1.19	0.61	-0.28	0.051

5.3 Kinematic patterns of the Abduction Task

During the Abduction Task, children with OBPP demonstrated increased variability in kinematic patterns across all joints and rotation axes (Figure 5.2). Two outliers demonstrated no elevation at the GH joint and minimal at the TH joint. There was no technical reason to exclude these data so they were retained. While some children with OBPP achieved similar degrees of TH/GH elevation compared with TDC, others exhibited reduced slope and ROM with a significant difference in both ROM (TH: TDC 123.11º; OBPP 70.96º; p < 0.001/GH TDC 81.3º; OBPP 37.33º; p <0.001) and PTA (TH: TDC -134.48º; OBPP -98.99º; p = 0.007/ GH; TDC -94.77º; -66.68º; p = 0.03). Children with OBPP tended to start with more GH elevation close to the frontal plane while the TH joint start position was similar in both groups. Both TDC and children with OBPP drifted into the scapular plane (54.12º TDC; 45.24º OBPP) as they reached PTA. Children with OBPP moved significantly less through GH POE (p = 0.006) compared with TDC. While both groups demonstrated active external rotation in the TH/GH joints during this task TH AR at both PTA and ROM were significantly different ($p = 0.05$ and $p < 0.001$ respectively). While not significant, on visual observation of the individual waveforms, children with OBPP adopted a more internally rotated posture at the GH joint with reduced ROM demonstrated by flatter slopes of individual curves (Figure 5.2).

ST M/L rotation ROM and pattern of movement were similar between groups. ROM in ST M/L rotation was similar at 43.55º(6.43º) for TDC and 43.36º(17.83º) in children with OBPP. However, the SD was larger for children with OBPP suggesting greater variation in its contribution to task performance across the group. Two children with OBPP followed the TDC's pattern of posterior tilt, however the majority maintained a more anteriorly tilted posture [mean (SD) at PTA [-10.56º(26.14º)] compared with TDC [6.65º(11.75º)]. The majority of participants with OBPP had small magnitudes of ROM in this rotation axis, the mean ROM being influenced by larger ROM achieved in two participants. A lot of variability was seen in the ST P/R graph with no specific pattern identifiable. No ST joint rotation axis was significantly different in this task (Table 5.2).

Children with OBPP had a reduced scapulohumeral rhythm (SHR) (1.04:1) compared with TDC (1.88:1) during completion of the Abduction Task. This was calculated using the degree of GH elevation and ST M/L rotation as per previous studies (Duff et al., 2007, Russo et al., 2014). The altered SHR was due to reduced GH elevation ROM 37.33º in OBPP compared with 81.3º in TDC, rather than excessive scapular movement. Overall six kinematic variables were significantly different between the groups (Table 5.2).

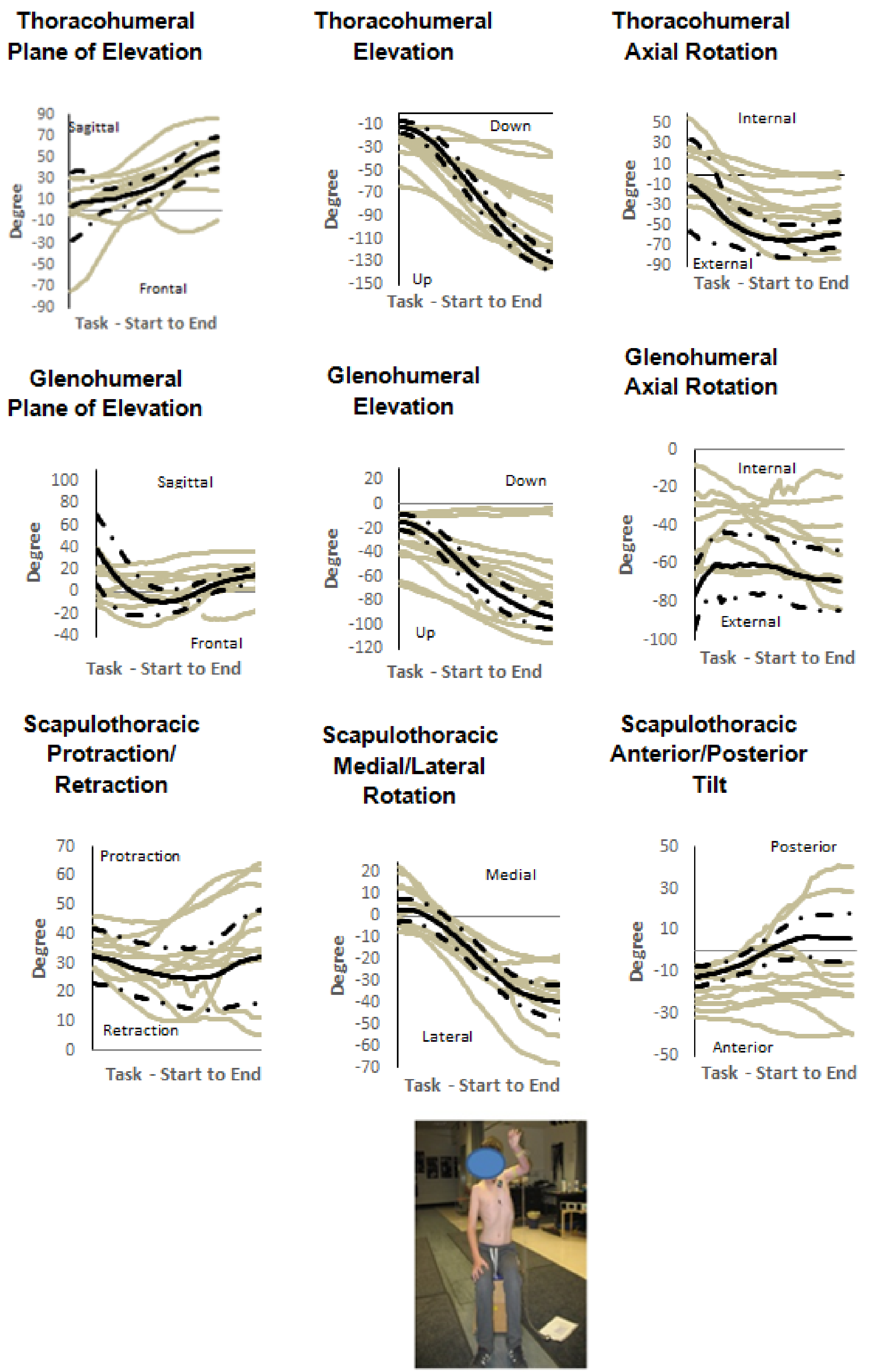


Figure 5.2: Abduction Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD); Obstetric Brachial Plexus Palsy

Table 5.2: Kinematic variables at point of task achievement and range of motion for the Abduction Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								**Range of Motion**							
	TDC		**OBPP**		**Difference**				**TDC**		**OBPP**		**Difference**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**
TH																
POE	54.12	13.57	45.24	26.69	-8.88	9.47	[a]	0.60[a]	62.46	14.06	50.86	20.15	-11.6	7.77	-28.07 → 4.86	0.16
ELE	-134.48	6.76	-98.99	34.92	35.49	10.74	[a]	0.002[a]*	123.11	9.21	70.96	31.81	-52.15	10.02	[a]	<0.001[a]*
AR	-59.1	12.39	-37.97	28.57	21.13	9.85	-0.28 →42.54	0.05	53.82	23.95	45.96	24.53	-86.83	13.79	-116.13 → 13.79	<.001
GH																
POE	15.72	5.67	14.42	14.97	-1.3	5.3	-13.11→ 10.5	0.81	52.88	21.15	23.42	14.32	-29.46	8.22	[a]	0.006[a]*
ELE	-94.77	10.71	-66.68	35.01	28.08	11.09	3.93 → 52.23	0.03*	81.3	8.64	37.33	20.3	-43.96	6.7	-58.36 → -29.57	<0.001*
AR	-66.87	16.93	-53.06	23.46	13.82	9.48	-6.45 → 34.08	0.17	29.17	15.2	22.92	16.46	-6.25	7.29	[a]	0.25[a]
ST																
P/R	31.98	16.31	37.98	21.03	6	8.7	-12.55 → 24.54	0.50	12.84	9.56	19.30	10.13	6.54	3.76	-1.92 → 14.83	0.12
M/L	-39.98	7.95	-37.39	16.77	2.6	6.13	-10.87 →16.06	0.68	43.55	6.43	43.36	17.83	-0.19	6.28	-14.22 → 13.83	0.98
A/P	6.65	11.75	-10.56	26.14	-17.21	9.06	-36.87 → 2.45	0.08	22.30	11.24	17.09	15.69	-5.21	6.1	-18.03 → 7.71	0.41

5.4 Kinematic patterns of the External Rotation Task

The External Rotation Task is a measure of active shoulder external rotation with the arm held by the side of the body. It demands very little movement into elevation or POE. Based on qualitative description of task performance and the large SD reported, it was evident that the isolation required to complete this task was challenging for both groups. TDC functioned closer to the sagittal plane and achieved better isolation, borne out by the narrow mean +/- 1SD waveform with the exception of a wider spread observed in TH POE at PTA (Figure 5.3). Both technical challenges with the "arm by side" position (Šenk and Chèze, 2006) and difficulty maintaining the elbow by the side without conscious effort may account for this pattern at PTA. In contrast, children with OBPP started closer to, or behind, the frontal plane with a consistently internally rotated posture in both TH/GH joints. A large SD was found in TH POE in both groups suggesting a lot of variability in task performance with different movement combinations used to achieve the task (Table 5.3). The TH joint was significantly more elevated in children with OBPP at PTA ($p = 0.002$).

Children with OBPP were biased towards internal rotation throughout the task with a significant difference in ROM and PTA of TH/GH AR (Figure 5.3 and Table 5.3). However, these findings may be confounded by technical problems encountered processing TDC data wherein a reversal of graph output (Chapter 3 Development of Methodology: Section 3.7.2.3; Appendix 3.7) was evident as the arm crossed midline. The correction method applied, multiply by -1, altered the discrete joint angles thereby influencing the difference in angle at PTA. Therefore, interpretation of differences in ROM is recommended, not PTA.

On observation of graphs, large postural variation of each ST joint rotation axis was evident, although in general children with OBPP started the task in a position of increased protraction, medial rotation and posterior tilt (Figure 5.3). Thereafter, they followed the TDC's pattern into retraction and lateral rotation with a contrasting bias towards anterior tilt. Retraction had the largest ROM in both groups with ST P/R at PTA the only significant variable of this joint ($p = 0.016$) (Table 5.3). While not significant, a postural alignment of scapular medial rotation throughout the movement suggests compensation for lack of true GH movement by fixing the scapula orientating the arm in space for apparent task completion.

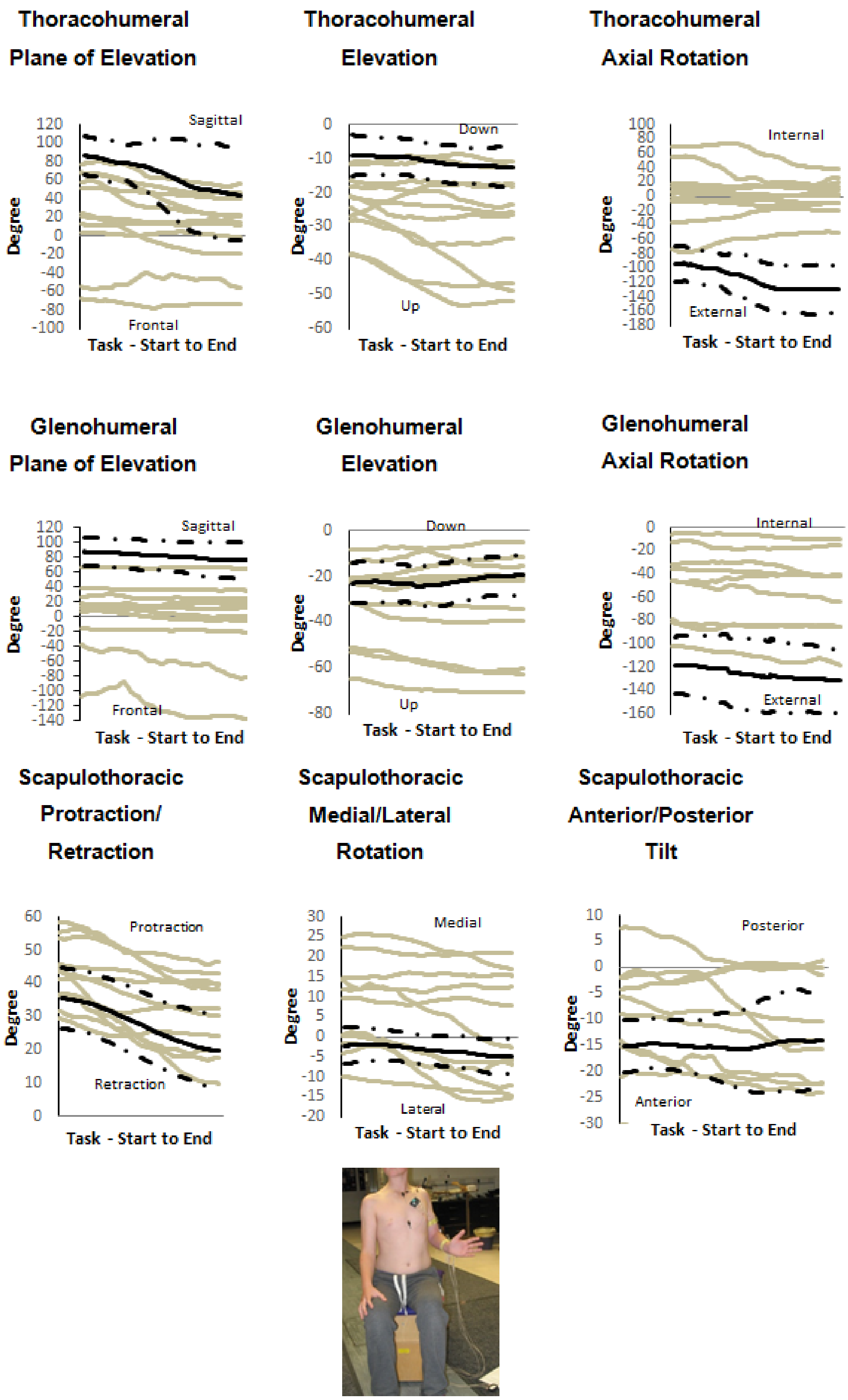


Figure 5.3: External Rotation Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD); Obstetric Brachial Plexus Palsy

Table 5.3: Kinematic variables at point of task achievement and range of motion for the External Rotation Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								**Range of Motion**							
	TDC		**OBPP**		**Difference**				**TDC**		**OBPP**		**Difference**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**
TH																
POE	47.41	45.13	5.63	40.83	-41.78	18.85	-81.33→-2.23	0.04*	60.17	26.34	21.01	15.72	-39.16	9.59	-59.66→-18.65	0.001*
ELE	-11.86	5.01	-28.7	14.6	-16.83	4.71	a	0.002*[a]	4.39	2.38	7.71	5.99	3.31	1.97	a	0.26[a]
AR	-129.91	26.94	2.2	24.11	132.12	11.2	a	<0.001*[a]	51.06	38.91	16.26	13.17	-34.8	12.93	a	0.008*[a]
GH																
POE	74.96	21.88	-6.31	57.66	-81.27	18.71	-121.67→-40.86	0.001*	23.44	16.85	15.87	16.90	-7.56	7.37	a	0.05*[a]
ELE	-18.32	8.2	-32.79	22.53	-14.47	7.27	a	0.25[a]	9.13	4.68	6.87	3.31	-2.27	1.79	-6.05→1.52	0.22
AR	-130.24	26.87	-46.07	45	84.17	16.57	48.78→119.56	<0.001*	26.29	14.15	12.38	9.4	-13.91	5.37	a	0.03*[a]
ST																
P/R	17.67	11.3	31.05	11.77	13.37	5.04	2.83→23.91	0.02*	17.35	6.59	12.73	7.52	-4.62	3.08	-11.07→1.82	0.15
M/L	-4.36	5	1.53	13.54	5.89	4.38	-3.58→15.35	0.20	5.72	3.99	7.25	5.79	1.52	2.15	a	0.76[a]
A/P	-12.77	7.17	-16.24	12.82	-3.47	4.48	-12.97→6.04	0.45	6.19	4.03	6.46	3.58	0.27	1.67	a	0.71[a]

5.5 Kinematic patterns of the Internal Rotation Rask

Based on visual observation of waveforms, similar kinematic patterns of slight TH/GH joint elevation in either the scapular or frontal POE were observed in both groups, with greater differences in TH/GH AR and ST joint rotation axes (Figure 5.4). Larger active ROM into internal rotation was demonstrated by the steeper slope of the curve in TDC and significantly more ROM (TH/GH $p < 0.001$) (Figure 5.4). As PTA was not significantly different but ROM was, this suggested a different start point for both groups with children with OBPP biased towards a relatively internally rotated posture. The gentler slopes were most apparent in GH POE and AR axes. While the gentler slopes were also typical of TH joint, more variability was present with some children with OBPP achieving greater ROM. One outlier in both TH/GH joints of children with OBPP impacted on the results increasing the mean magnitude of ROM achieved. This can be clearly seen in the graphs with the majority of children with OBPP exhibiting reduced ROM compared with TDC. There was no technical reason to exclude this participant. However, due to its obvious difference one can still interpret the overall trend of children with OBPP from the graphs.

The gentle slopes of the ST rotation axes in both groups suggest little ROM was required at this joint for task completion. However, children with OBPP had significantly larger ROM in all rotation axes (Table 5.4). Apart from ST P/R, where both groups have a wide variability in postural alignment, children with OBPP had a greater spread of postural attitudes. This is especially evident in ST M/L rotation [mean (SD) 12.11º(10.22º)] and A/P tilt [-17.35º(10.88º)]. ST M/L rotation was significantly different at PTA ($p = 0.003$) where children with OBPP were more medially rotated for task duration. There was a slight trend towards more anterior tilt in children with OBPP compared with a tendency towards posterior tilt in TDC.

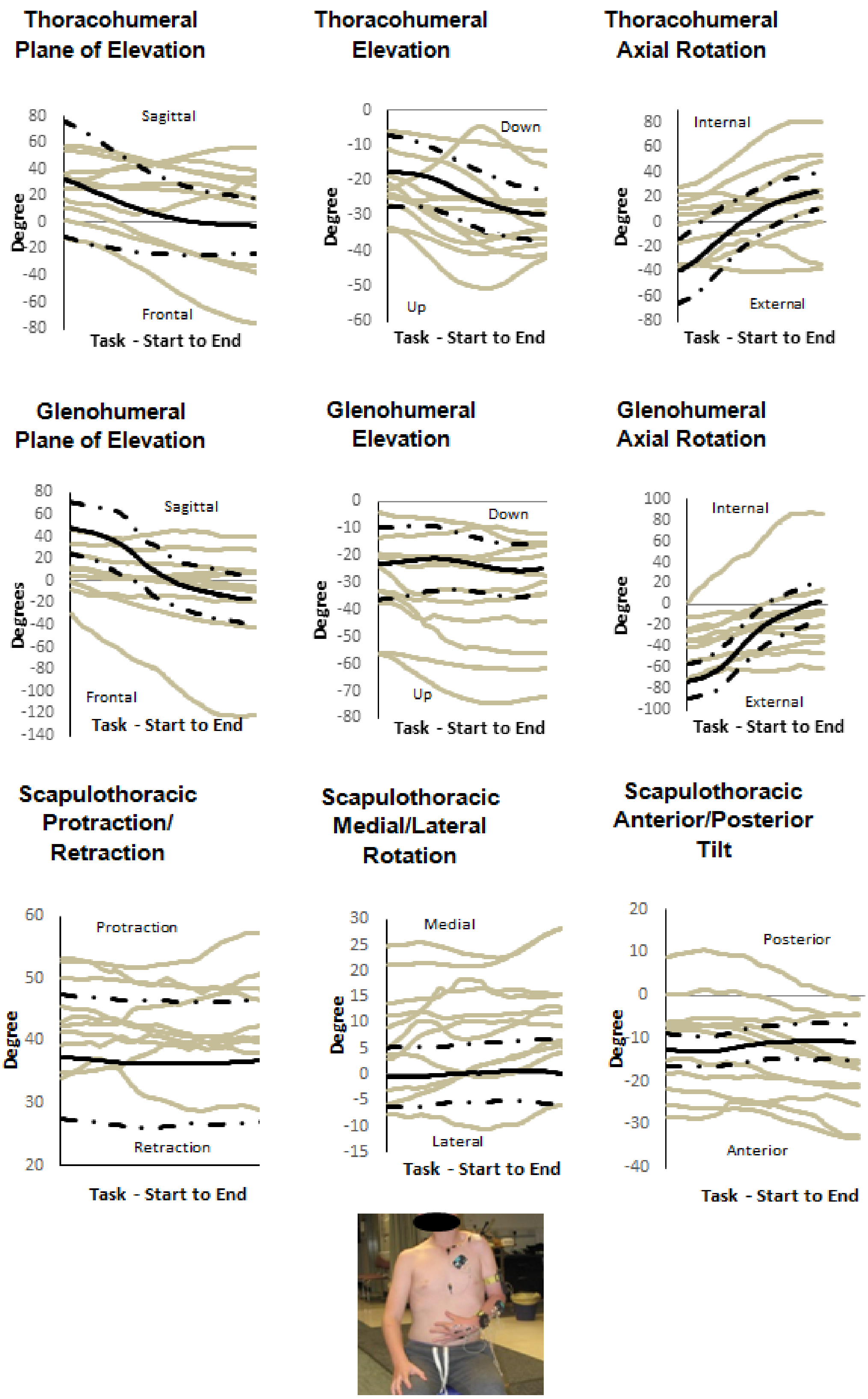


Figure 5.4: Internal Rotation Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD); Obstetric Brachial Plexus Palsy

Table 5.4: Kinematic variables at point of task achievement and range of motion for the Internal Rotation Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								Range of Motion							
	TDC		OBPP		Difference				TDC		OBPP		Difference			
	Mean	SD	Mean	SD	Mean	SD	95% CI of difference	p value	Mean	SD	Mean	SD	Mean	SD	95% CI of difference	p value
TH																
POE	0.93	17.05	4.84	42.23	3.91	14.65	-27.91→35.72	0.79	50.98	20.64	32.11	16.29	-18.87	8.9	-38.14→0.40	0.05*
ELE	-29.21	7.18	-30.36	9.83	-1.16	3.73	[a]	0.62[a]	12.61	5.84	11.77	6.71	-0.84	2.74	-6.58→4.90	0.76
AR	24.83	14.58	18.97	37.14	-5.85	12.83	-33.74→22.04	0.66	64.97	17.77	27.51	17.19	-37.46	8.31	-55.17→-19.74	<0.001*
GH																
POE	-19.47	22.8	-10.75	45.41	8.71	16.25	[a]	0.17[a]	67.79	29.25	23.09	26.59	-44.7	12.287	[a]	0.003*[a]
ELE	-24.61	8.58	-35.35	20.1	-10.74	6.72	[a]	0.36[a]	8.97	5.02	9.31	6.33	0.34	2.48	[a]	0.94[a]
AR	6.01	21.54	-11.25	40.61	-17.26	14.93	-49.24→14.72	0.27	76.67	15.2	26.54	22.41	-50.13	8.89	-69.01→-31.24	<0.001*
ST																
P/R	36.53	9.97	43.97	8.73	7.44	4.11	-1.19→16.07	0.09	2.72	1.14	4.95	2.50	2.22	0.84	[a]	0.03*[a]
M/L	-0.11	5.58	12.11	10.22	12.22	3.55	4.68→19.76	0.003*	2.55	1.60	6.80	3.02	4.25	1.04	2.04→6.47	0.001*
A/P	-10.79	4.32	-17.35	10.88	-6.56	3.55	-14.22→1.10	0.09	3.51	0.90	6.83	3.02	3.31	0.95	1.24→5.39	0.005*

5.6 Kinematic patterns of the Hand-to-Mouth Task

Greater variability in strategies used by the affected group to achieve this task was demonstrated by wider SD in ROM, particularly in TH/GH elevation axes (Table 5.5). Magnitude of ROM was not significantly different between the groups. However, the significant difference found between all TH joint rotation axes and two GH joint rotation axes at PTA implied different strategies were adopted by both groups to achieve the task. The graphs clearly demonstrated the compensatory pattern adopted by children with OBPP to achieve the Hand-to-Mouth Task, clinically known as the "trumpet posture" (Figure 5.5). This posture was characterised by a significantly larger degree of TH/GH elevation at PTA ($p = 0.013$) biased towards the scapular plane at the TH joint ($p < 0.001$) and the coronal plane in the GH joint ($p < 0.001$) (Table 5.5). This strategy compensated for reduced GH joint external rotation which was evident in the AR graphs with a significantly altered posture of internal rotation seen at both TH/GH joints ($p = 0.016$/$p < 0.001$ respectively).

Children with OBPP had varied ST joint motion but a bias towards lateral rotation, posterior tilt and protraction was evident. Both ROM of ST M/L rotation and ST A/P tilt in children with OBPP were significantly greater than TDC [OBPP 16.06º(6.45º); TDC 0.90º(3.34º) and OBPP 10.47º(5.77º); TDC 4.69º(1.75º) respectively]. The increased ROM in both these rotation axes in the affected group suggested alternative strategies were adopted to compensate for reduced ability. As muscle activity was not examined in this study the exact deficiencies can only be implied not confirmed. Similar elbow joint movement patterns of flexion and supination were observed in both groups. Three outliers in the affected group may have contributed to the significantly reduced supination ROM ($p = 0.048$). However, both groups demonstrated large variability in this movement with SD of 22.88º in TDC and 25.58º in children with OBPP (Table 5.5).

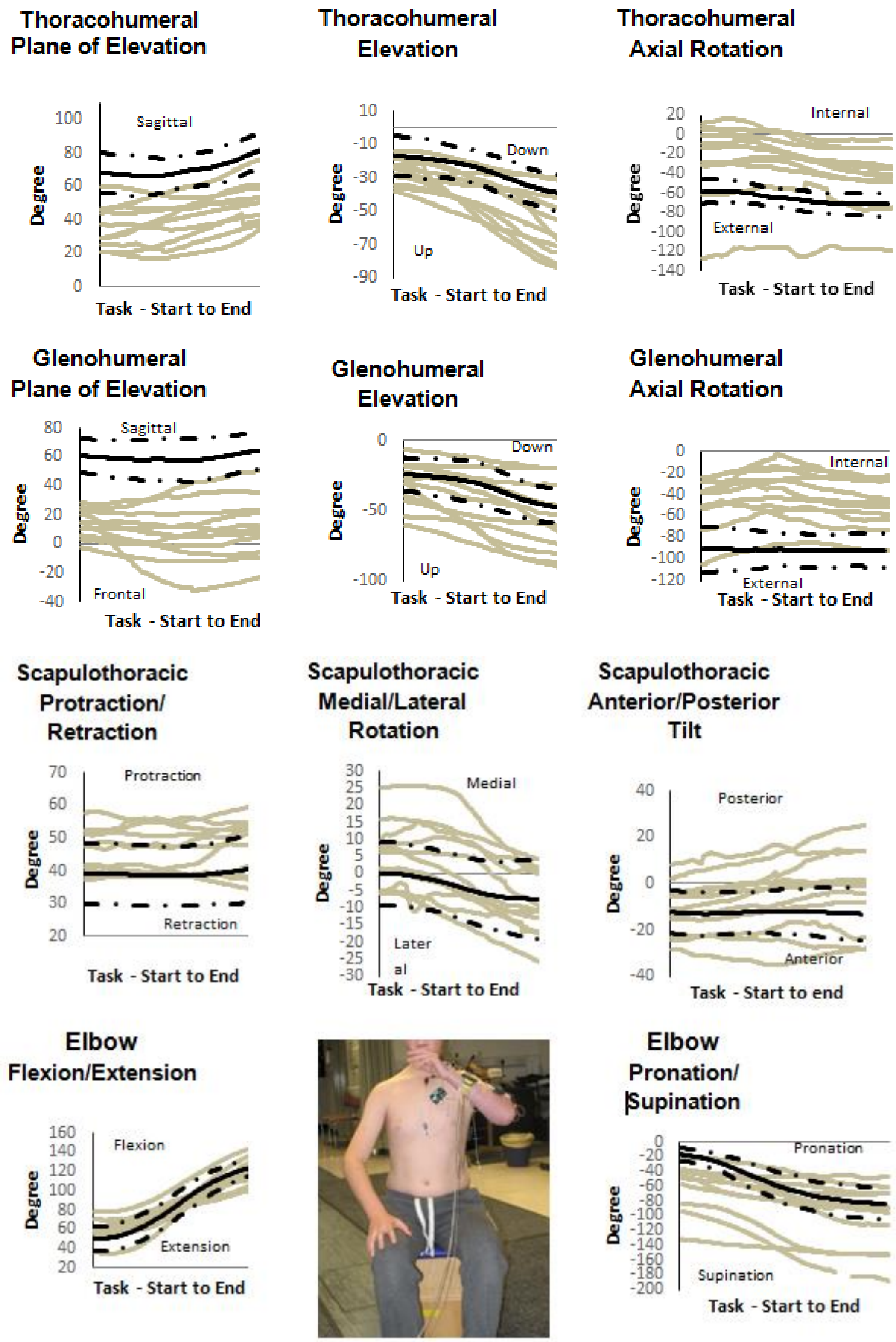


Figure 5.5: Hand-to-Mouth Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD);

Obstetric Brachial Plexus Palsy

Table 5.5: Kinematic variables at point of task achievement and range of motion for the Hand-to-Mouth Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; F/E: Flexion/Extension; P/S: Pronation/Supination; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								Range of Motion							
	TDC		OBPP		Difference				TDC		OBPP		Difference			
	Mean	SD	Mean	SD	Mean	SD	95% CI of difference	p value	Mean	SD	Mean	SD	Mean	SD	95% CI of difference	p value
TH																
POE	92.81	12.79	58.22	13.36	-34.59	6	-47.25→-21.92	<0.001*	30.09	19.91	25.29	11.48	-4.81	7.56	-21.21→11.6	0.54
ELE	-41.01	8.27	-64.86	21.18	-23.85	6.9	a	0.01*[a]	24.72	5.07	38.63	18.46	13.91	5.79	a	0.13[a]
AR	-71.89	13.25	-43.37	31.41	28.51	10.45	6.1→50.93	0.02*	20.15	18.27	23.57	9.33	3.42	6.71	-11.29→18.13	0.62
GH																
POE	69.51	16.56	14.14	19.33	-55.37	7.84	-71.77→-38.96	<0.001*	18.45	15.16	16.05	9.64	-2.39	5.61	a	0.92[a]
ELE	-49.06	11.19	-58.57	25.54	-9.52	8.47	-27.7→8.66	0.28	25.05	7.65	26.87	15.65	1.82	5.30	-9.49→13.13	0.74
AR	-91.85	15.01	-48.68	22.16	43.17	8.2	25.93→60.41	<0.001*	16.15	7.23	17.79	7.87	1.64	3.29	-5.25→8.54	0.62
ST																
P/R	41.44	12	48.42	11.5	6.97	5.14	-3.8→17.75	0.19	5.32	2.38	7.70	5.59	2.38	1.85	a	0.43[a]
M/L	-7.86	5.54	-9.23	9.55	-1.37	3.37	-8.51→5.77	0.69	0.90	3.34	16.06	6.45	7.66	2.21	a	0.004*[a]
A/P	-13.17	6.34	-3.44	17.64	9.73	5.68	-2.57→22.04	0.11	4.69	1.75	10.47	5.77	5.78	1.83	a	0.001*[a]
Elbow																
F/E	132.3	7.07	132.16	12.38	-0.14	4.35	-9.35→9.08	0.98	82.49	12.55	72.7	17.16	-9.79	6.52	-23.48→3.90	0.15
P/S	-83.37	22.16	-102.59	44.48	-19.22	15.13	-51.48→13.04	0.22	66.89	22.88	44.53	25.58	-22.36	10.57	-44.49→-0.22	0.05*

5.7 Kinematic patterns of the Hand-to-Neck Task

Both groups followed a similar pattern of movement to achieve this task, although some differences in performance were noted (Figure 5.6). TDC elevated the TH/GH joints starting from the sagittal POE moving towards the scapular plane through external rotation. In contrast, children with OBPP were consistently more internally rotated starting in the TH/GH frontal POE. For PTA only GH AR was significantly different, with children with OBPP more internally rotated ($p = 0.006$) (Table 5.6). However, significantly reduced ROM of TH/GH elevation ($p = 0.021$/$p < 0.001$ respectively) and GH POE ($p = 0.004$) was noted in children with OBPP. Start point was not statistically analysed, however it was evident from the graphs that children with OBPP started from a more frontally orientated upper arm position. Based on this trend and the non-significant difference at PTA, the altered start positions contributed to the reduced ROM in children with OBPP. It was interesting to note that the largest ROM of TH elevation in children with OBPP (82.77º ±24.92º) was in this task which was ~10º more than the Abduction Task (TH (70.96º ±31.81º).

For both groups the ST joint moved through a pattern of retraction, lateral rotation and posterior tilt. While no significant difference was found between the groups more variation was seen at PTA in all rotation axes in children with OBPP (Figure 5.6). Some individuals with OBPP had excessive movement into these patterns, while others were reduced. This may indicate that in children who are less affected the scapula functioned appropriately, while children more severely affected adopted alternate strategies to achieve the task. Waveform trends were similar at the elbow joint with gradual initial flexion, indicated by the flatter gradient, and a steeper slope as they approached the neck suggesting greater elbow flexion. More supination was evident at the start with flattening of the curve at task end in both groups, although more variability was seen in the affected group with significantly reduced ROM of supination ($p = 0.029$).

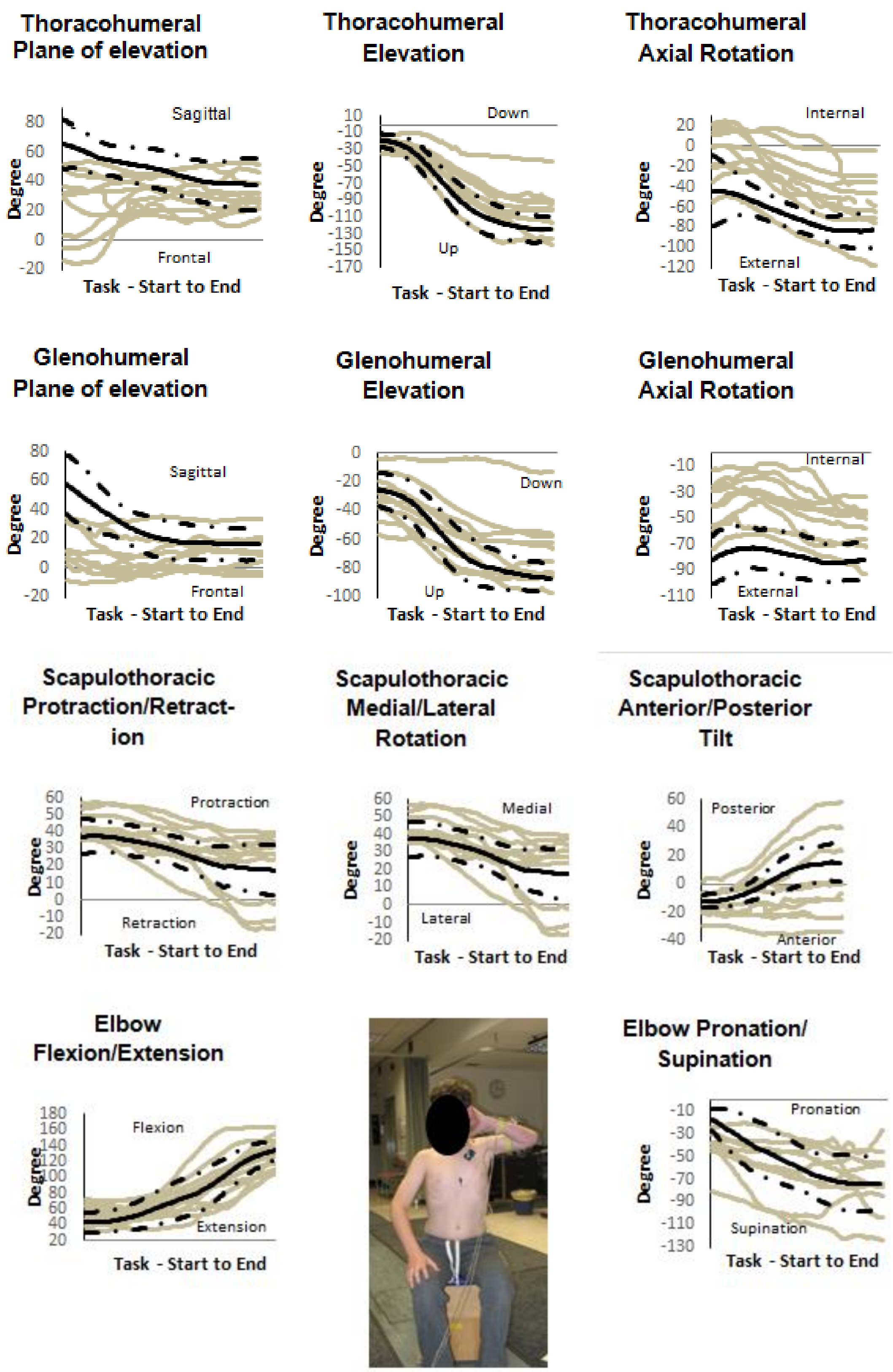


Figure 5.6: Hand-to-Neck Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD);

Obstetric Brachial Plexus Palsy

Table 5.6: Kinematic variables at point of task achievement and range of motion for the Hand-to-Neck Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; F/E: Flexion/Extension; P/S: Pronation/Supination; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								**Range of Motion**							
	TDC		**OBPP**		**Difference**				**TDC**		**OBPP**		**Difference**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**
TH																
POE	38.72	15.74	30.82	11.75	-7.9	6.21	-21.03→5.23	.22	29.34	19.19	23.7	10.82	-5.65	6.97	-20.57→9.27	.43
ELE	-123.54	15.52	-103.74	28.48	19.80	10.26	[a]	.11[a]	105.85	14.38	82.77	24.92	-23.58	9.10	-43.05→-4.12	.02*
AR	-80.36	17.61	-55.63	32.31	24.73	12.12	-1.67→51.12	.06	49.21	26.45	51.89	22.87	2.69	11.06	-20.58→25.95	.81
GH																
POE	16.42	10.27	12.08	12.48	-4.35	5.28	-15.56→6.87	.42	43.65	20.12	18.35	10.81	-25.30	7.31	-40.48→-9.63	.004*
ELE	-85.83	11.14	-68.35	23.70	17.48	8.28	-0.44→35.41	.06	62.13	6.32	39.63	12.41	-22.5	4.4	-31.99→-13.01	<.001*
AR	-80.11	14.58	-55.63	17.96	23.8	7.56	7.73→39.86	.006*	26.58	14.05	29.48	10.50	2.9	5.66	-9.06→14.86	.62
ST																
P/R	16.61	13.98	19.68	20.54	3.07	7.86	-13.6→19.74	.70	22.08	12.7	27.79	16.73	5.72	6.64	[a]	.35[a]
M/L	-35.33	6.48	-33.33	11.98	2.0	4.31	-7.24→11.25	.65	34.55	7.73	42.89	14.59	8.33	5.22	-2.89→19.55	.13
A/P	13.84	12.69	4.94	29.91	-8.9	10.75	-32.68→14.88	.43	28.14	12.21	18.66	19.37	-9.49	7.24	-24.91→5.94	.21
Elbow																
F/E	137.01	7.44	131.71	19.37	-5.30	6.3	-18.89→8.29	.42	95.42	11.43	81.26	23.36	-14.16	7.92	[a]	.05[a]
P/S	-73.67	23.38	-71.96	29.93	1.71	12.66	-25.26→28.67	.89	60.1	19.12	39.38	17.34	-20.72	8.6	-38.97→-2.46	.03*

5.8 Kinematic patterns of the Hand-to-Spine Task

As with all other tasks, children with OBPP demonstrated more variability in pattern and ROM achieved in the Hand-to-Spine Task (Figure 5.7). This was demonstrated by larger SD across all joints (Table 5.7). This task had the highest number of significantly different variables in both PTA and ROM between groups, predominantly in the TH/GH joints (Table 5.7). Children with OBPP moved significantly less in all rotation axes with TDC demonstrating greater internal rotation ($p < 0.001$) and movement beyond the frontal plane into what is clinically understood to be extension ($p = 0.004$). In contrast to the previous task, Hand-to-Neck, the start point for this task had a narrower variation for both groups. However, PTA was more variable in children with OBPP across all joint rotation axes. The variability at PTA indicated difficulty with this task in children with OBPP. The ability to "extend" the joint was present in some children while others hardly moved at all, evident by the flatness of individual curves. About three children demonstrated active internal rotation during the task while others had very little ROM (Figure 5.7). As a group, children with OBPP had significantly less active TH/GH internal rotation ($p < 0.001$). This further emphasised that while the children with OBPP exhibited a bias towards an internally rotated posture their ability to move through ROM was compromised.

GH joint elevation at PTA was not significantly different between groups but ROM was significantly reduced in children with OBPP ($p = 0.014$). Based on observation of the graphs, postural alignment of GH joint elevation in children with OBPP varied from ~ 5º to 60º of elevation but with very little active movement throughout the task. This would have influenced discrete angles at PTA with the consistently reduced ROM contributing to the significant difference between groups in ROM. The mean ROM of GH AR for TDC was large at 133.76º(42.12º). This was possibly related to the orientation of the humerus as it has been found that maximal ROM of a joint was dependent on its position with larger internal rotation possible when the humerus was in extension compared with 90º abduction (Magermans et al., 2005).

While greater variation was evident in the affected group, especially in ST A/P tilt, the general movement patterns of the ST joint were similar between both groups (Figure 5.7). This is borne out by the fact that only ST P/R at PTA was significantly different with TDC being more retracted at PTA ($p = 0.003$). The dominant pattern was one of initial retraction followed by a reversal towards protraction half way through the task. The ability to achieve this task in the presence of deficient GH joint motion is very difficult, resulting in the affected group being more functionally compromised. This task demonstrated the greatest variation in elbow motion in both groups with wide SD evident (Table 5.7). As with the other two tasks, only elbow P/S was significantly different in ROM with more supination achieved by TDC. However, results of this joint were compromised by issues with marker view during task performance.

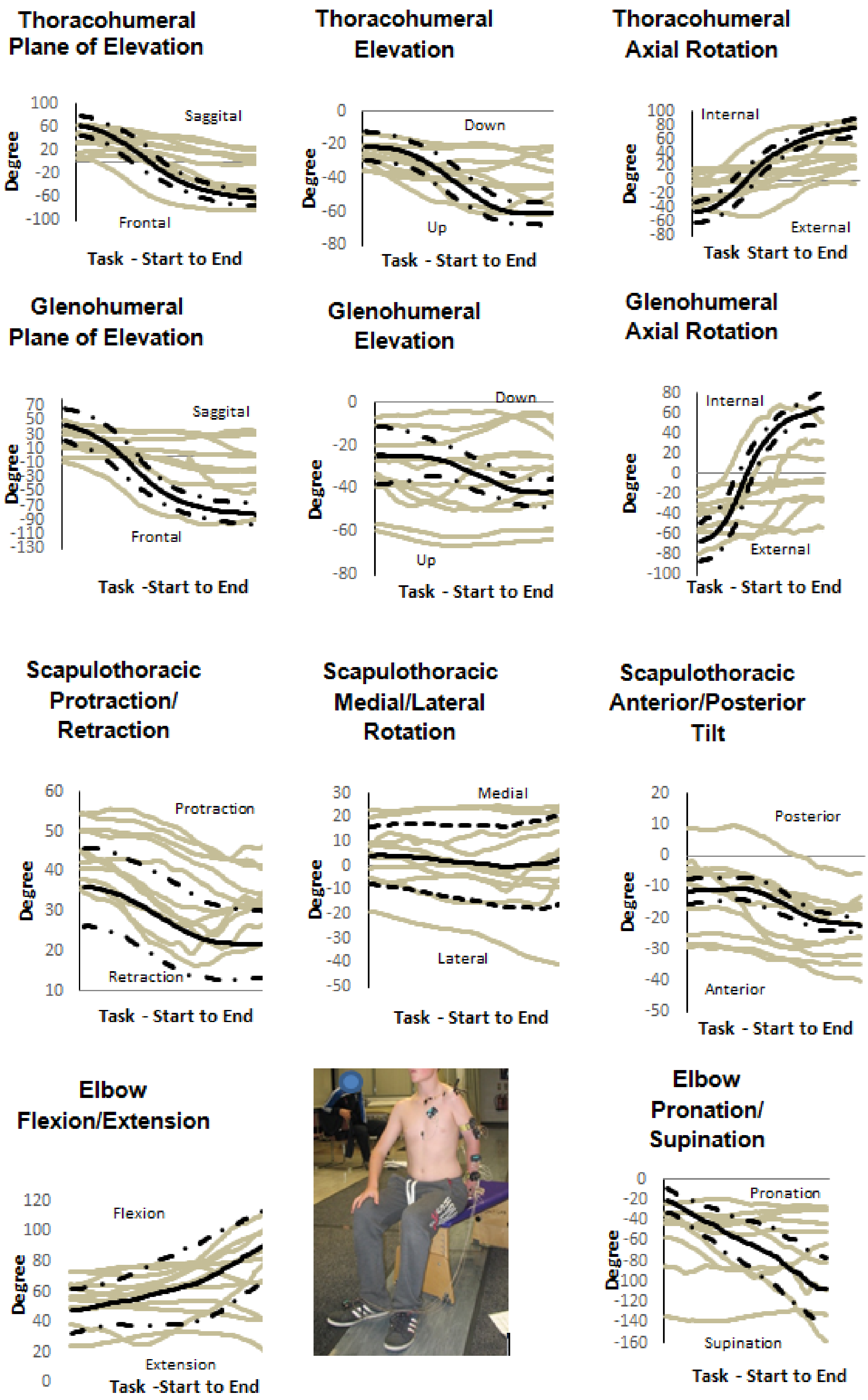


Figure 5.7: Hand-to-Spine Task

Mean typically developing children (TDC); ±1 Standard Deviation (SD); Obstetric Brachial Plexus Palsy

Table 5.7: Kinematic variables at point of task achievement and range of motion for the Hand-to-Spine Task in typically developing children and children with obstetric brachial plexus palsy and concurrent significant p-values of group comparison

Units of measurement: degrees; PTA: Point of Task Achievement; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; SD: Standard Deviation; 95% CI: Confidence Interval; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of Elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; F/E: Flexion/Extension; P/S: Pronation/Supination; *: significant p-values; a: denotes non-normally distributed data tested with a Wilcoxon signed-rank test; confidence intervals were not calculated in this instance

	PTA Angles								**Range of Motion**							
	TDC		**OBPP**		**Difference**				**TDC**		**OBPP**		**Difference**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**95% CI of difference**	**p value**
TH																
POE	-67.15	12.88	-20.93	38.59	46.23	13.03	17.68→74.77	0.004*	129.11	21.62	60.09	31.55	-69.02	12.57	-95.71→-42.34	<0.001*
ELE	-61.29	8.11	-38.8	15.5	22.5	5.33	11.16→33.83	0.001*	42.95	12.31	18.56	11.54	-24.39	5.22	-35.34→-13.44	<0.00*
AR	75.98	12.82	41.97	29.62	-34.01	10.40	-56.52→-11.49	0.006*	122.55	18.21	57.12	30.26	-65.43	11.53	-90.01→-40.84	<0.001*
GH																
POE	-84.93	17.09	-14.53	38.1	70.4	14.07	39.56→101.23	<0.001*	128.25	32.33	39.51	28.23	-88.74	14.81	-120.49→57	<0.001*
ELE	-39.99	7.09	-34.38	18.23	5.61	5.94	-7.20→18.41	0.36	23.04	9.89	12.96	5.91	-10.08	3.6	-17.78→-2.38	0.01
AR	65.6	16.13	-5.09	32.16	-70.69	12.14	-97.13→-44.25	<0.001*	133.76	30.25	42.12	28.94	-91.64	14.40	-122.42→-60.87	<0.001*
ST																
P/R	22	8.9	34.99	6.96	12.99	3.63	5.24→20.74	0.003*	15.53	5.89	15.32	5.10	-0.21	2.49	-5.49→5.08	0.94
M/L	7.63	7.17	3.33	18.94	-4.29	6.15	[a]	0.76[a]	9.42	3.92	10.65	5.94	1.23	2.18	-3.36→5.81	0.58
A/P	-22.44	2.44	-22.70	10.3	-0.26	3.2	-7.29→6.77	0.94	13.66	4.44	13.14	4.91	0.52	2.04	-4.79→3.75	0.80
Elbow																
F/E	92.71	27.44	-77.1	33.26	-15.61	13.26	[a]	0.2[a]	47.44	22.78	31.39	23.61	-16.05	10.13	-37.25→5.15	0.13
P/S	-109.15	29.96	-69.92	44.79	39.23	16.5	4.51→73.96	0.03*	91.03	32.36	27.31	27.17	-63.71	13.11	-91.28→-36.14	<0.001*

5.9 Summary of kinematic differences between groups

This section presents a brief summary of the kinematic findings of this research (Table 5.8). In general, children with OBPP had more variation in pattern and ROM across all joints and rotation axes during task performance. This was characterised by wider SD and several outliers. Significant differences were not consistent across ROM and PTA due to altered start positions observed between groups. With the exception of the Hand-to-Spine Task, the upper arm in children with OBPP was always orientated towards the frontal POE in both TH/GH joints at the start. For all tasks both TH/GH joints were more internally rotated at start point and PTA with the exception of the Internal Rotation and Hand-to-Spine Tasks. For both these tasks, TDC moved significantly more into actual internal rotation than children with OBPP resulting in a more internally rotated position at PTA.

Children with OBPP were observed to demonstrate more TH/GH elevation than TDC in the tasks that required very little GH/TH elevation. In contrast, for the tasks that demanded more TH/GH elevation (Abduction/Hand-to-Neck) children with OBPP followed a similar pattern of movement but with reduced ROM achieved. While not a significant finding, on visual inspection of the graphs the ST joint in children with OBPP was more protracted and medially rotated in all tasks. ST A/P tilt was more variable throughout the tasks. Only the Internal Rotation and Hand-to-Mouth Tasks demonstrated a significant difference in ROM of ST joint between groups. For the elbow joint significantly reduced supination was observed in all three tasks analysed.

In conclusion deficits in GH joint movement were the largest contributors to altered patterns of task performance with significant differences seen between groups in all tasks. The lack of movement into GH external rotation, elevation and extension contributed to the frontal plane, internal rotation posture and altered SHR. ST joint motion while more varied in presentation was not found to be significantly different between groups in the majority of tasks.

Table 5.8: Summary of significant variables between typically developing children and children with obstetric brachial plexus palsy

Units of measurement: p-values (significance p < 0.05); PTA: Point of task achievement; TH: Thoracohumeral; GH: Glenohumeral; ST: Scapulothoracic; POE: Plane of elevation; ELE: Elevation; AR: Axial Rotation; P/R: Protraction/Retraction; M/L: Medial/Lateral Rotation; A/P: Anterior/Posterior tilt; P/S: Pronation/Supination

	TH POE	**TH ELE**	**TH AR**	**GH POE**	**GH ELE**	**GH AR**	**ST P/R**	**ST M/L**	**ST A/P**	**Elbow P/S**
Abduction										
PTA	-	0.002	0.05	-	0.03	-	-	-	-	
ROM	-	<0.001	<0.001	0.006	0.006	-	-	-	-	
External Rotation										
PTA	0.04	0.002	<0.001	0.001	-	<0.001	0.02	-	-	
ROM	0.001	-	0.008	0.05	-	0.03	-	-	-	
Internal Rotation										
PTA	-	-	-	-	-	-	-	0.003	-	
ROM	0.05	-	<0.001	0.003	-	<0.001	0.03	0.001	0.005	
Hand-to-Mouth										
PTA	<.0001	0.01	0.02	<0.0001	-	<0.001	-	-	-	-
ROM	-	-	-	-	-	-	-	0.004	0.001	0.05
Hand-to-Neck										
PTA	-	-	-	-	-	0.006	-	-	-	-
ROM	-	0.02	-	0.004	<0.001	-	-	-	-	0.03
Hand-to-Spine										
PTA	0.004	0.001	0.006	<0.001	-	<0.001	0.003	-	-	0.03
ROM	<0.001	<0.001	<0.001	<0.001	0.01	<0.001	-	-	-	<0.001

5.10 Discussion

3D analysis of kinematic characteristics of dynamic functional task performance in children with OBPP, incorporating the scapula, has not been reported in the literature. This was the first study to address this gap thereby contributing novel information to the field while acknowledging limitations in interpretation identified in the reliability study. The aims of the kinematic study were to measure which 3D spatiotemporal and kinematic parameters differentiated upper limb movement characteristics of children with OBPP from TDC. The hypothesis that to achieve functional tasks, children with OBPP would move faster with more scapular movement was not accepted. While TDC did move faster the difference was not significant and excess scapular movement was not a consistent feature in task performance of children with OBPP. The hypothesis of a bias towards internal rotation was accepted as this posture was evident in all tasks. As the clinical application of 3D-ULMA in children with OBPP was the main interest of this research, establishing its test-retest reliability in this population, as presented in Chapter 4, was critical. This research did not specifically examine test-retest reliability of TDC as it has already been established in the literature (Vanezis et al., 2015, Lempereur et al., 2012, Jaspers et al., 2011c, Reid et al., 2010). This previous work permitted comparison of kinematic patterns of children with OBPP in this study with due consideration to the limitations identified (i.e. lower test-retest reliability in functional tasks (Lempereur et al., 2012), movements with smaller ranges of motion (Jaspers et al., 2011c; Reid et al., 2010), more refined movements e.g. elbow P/S (Vanezis et al., 2015) and humeral axial rotation. All results were interpreted with respect to these limitations. The following section discusses the findings of this research with respect to its clinical implications and where possible in the context of existing research.

5.10.1 Spatiotemporal parameters

It was found that TDC on average took longer to perform each task compared with children with OBPP. However, the difference in duration was not significant. No other study has examined the spatiotemporal parameters of functional task performance in children with OBPP. Based on clinical observation, it had been hypothesised that children with OBPP would perform the tasks of the modified Mallet scale faster than TDC. This was proposed based on the premise that to compensate for reduced power and deficits in certain movements, momentum produced from greater speed would improve task achievement. A contrasting finding was identified in a research study comparing spatiotemporal parameters of task performance in TDC with children with HCP. A significant difference between the groups was found with the affected group presenting with significantly longer task duration (Jaspers et al., 2011a). The findings of the current study do not support the hypothesis that children with OBPP move faster than TDC.

5.10.2 Thoracohumeral joint

While not statistically different in all tasks or rotation axes, TH ROM was in general lower in children with OBPP compared with TDC. The only tasks with a larger ROM recorded in children with OBPP were the External Rotation Task (TH elevation: OBPP 7.71º; TDC 4.39º; $p = 0.261$) or the Hand-to-Mouth Task (TH elevation: OBPP 38.63º; TDC 24.72º; $p = 0.13$). Both these tasks require GH external rotation which was deficient in children with OBPP thereby suggesting that increased TH elevation was a compensatory strategy. The current research cannot definitively conclude this as the difference was insignificant but further research with larger numbers may provide more evidence to support this theory.

Several studies have examined TH kinematics in children with OBPP performing functional tasks. Direct comparisons with this study were not possible due to methodological differences, namely tasks analysed, marker placement, coordinate system and joint rotation sequence definitions. However, similar to this research they highlighted kinematic differences in task performance between TDC and children with OBPP that were not captured by clinical examination (Fitoussi et al., 2009). The first observation of these studies; reduced ROM in the affected group agreed with this research's findings. Reduced TH motion in all rotation axes in particular during Hand-to-Mouth Task and moving an object across a table were found in Fitoussi et al. (2009) and consistently reduced shoulder external rotation during all tasks analysed (hand to top of head, high overhead reach and hand to back pocket) was found by Mosqueda et al. (2004). However, despite having shoulder weakness, in some tasks children with OBPP demonstrated greater ROM than TDC in certain rotations e.g. greater internal rotation in hand to back pocket (Mosqueda et al., 2004). This was in contrast with this research where children with OBPP had significantly reduced internal rotation in the Hand-to-Spine task ($p < 0.001$).

This leads to the second main observation from existing literature, altered patterns of movement between TDC and children with OBPP. This was evident with statistically significant increased neck flexion ($p < 0.05$) in children with OBPP during hand to head movement and increased shoulder abduction in hand to back pocket despite not achieving the end point of this task (Mosqueda et al., 2004). In addition, increased elbow ROM was observed in the high reach task, most likely to compensate for reduced shoulder flexion (Mosqueda et al., 2004). While this may seem counterintuitive, in that increased elbow extension generally allows for higher reach capacity, this is only true when the GH joint has achieved maximum elevation. An optical 180º of TH elevation can be obtained in the presence of limited GH joint motion by increasing elbow flexion to orientate the hand closer to the target point (Magermans et al., 2005). Neither neck nor thorax kinematics were analysed in this research study, but qualitative observation suggested compensatory movements in both segments contributed to task performance in children with OBPP. For the majority of tasks, a significant difference was found at PTA for TH joint rotation axes suggesting the need to adopt different strategies for task completion. Despite a lack of significant difference in the TH joint at PTA in the Hand-to-Neck and Internal Rotation Tasks, significant differences were noted in ROM suggesting alternate strategies were used with possible compensatory thorax or neck movement.

5.10.3 Glenohumeral joint motion

Efforts to analyse dynamic GH/ST joint kinematics using 3D motion analysis have gained momentum in recent years, however challenges in obtaining valid and reliable analysis remain. A recent study by Vanezis et al. (2015) concluded that TH motion was more reliable than GH or ST joints during dynamic 3D motion analysis. While acknowledging this limitation, distinguishing between the individual joints of the shoulder is valuable in increasing knowledge and understanding of typical and atypical function.

GH joint contribution to upper limb motion in children with OBPP has been explored during arm elevation by Duff et al. (2007) and at PTA in the modified Mallet scale by Russo et al. (2014). Both studies concurred with the findings of this research, that reduced magnitude of GH joint motion was the main contributor to altered kinematic patterns of the upper limb in children with OBPP; this is further explored in the following sections.

5.10.3.1 Scapulohumeral rhythm

Optimal shoulder function depends on the coordinated motion of the GH and ST joints. The SHR, defined as the ratio between GH elevation and ST lateral rotation, was reported as 2:1 in healthy adults (Inman et al., 1996). This ratio is used regularly in clinical practice to analyse shoulder kinematics and dyskinesia. While this ratio is generally accepted, it has been found to be influenced by POE (Giphart et al., 2013), age (Dayanidhi et al., 2005) and population (Duff et al., 2007, Russo et al., 2014). Consideration of these factors is important when analysing presentation of altered SHR in different populations.

While methodological differences impeded direct comparison between research studies exploration of their findings revealed similar trends. Russo et al. (2014) evaluated GH/ST contributions to the PTA of the tasks of the modified Mallet scale in 20 children with OBPP with 6 unaffected limbs used as controls. This information was acquired through static data acquisition via a scapula locator using ISB recommended coordinate systems but the helical angle method to define ST/GH joint motion. It was concluded that GH motion was significantly reduced in children with OBPP at PTA in all modified Mallet positions and that this impacted directly on reduced SHR in the Abduction Task (GH joint abduction/adduction $p = 0.006$) (Table 5.9).

Table 5.9: Mean range of motion (standard deviation) and scapulohumeral rhythm for typically developing children and children with obstetric brachial plexus palsy during Abduction Task comparison with previous studies

Units of measurement: degrees; GHJ: Glenohumeral Joint; THJ: Thoracohumeral Joint; STJ: Scapulothoracic Joint; LR: Lateral Rotation; SHR: Scapulohumeral Rhythm; TDC: Typically Developing Children; OBPP: Obstetric Brachial Plexus Palsy; Group 1: ≤75º elevation; Group 2: >75º elevation): Group A: Erb's Palsy; Group B: Extended Erb's Palsy; NR: Not reported

	Current research		**Russo et al. (2014)**			**Duff et al. (2007)**		
	TDC	OBPP	TDC	Group A	Group B	TDC	Group 1	Group 2
GHJ Elevation	82.3(8.64)	37.33(20.3)	38.8(18.5)	15.2(17.4)	1.4(22.9)	NR	NR	NR
STJ: LR	43.55(6.43)	43.36(17.83)	35.1(13)	31.5(13.4)	41.4(7.2)	NR	NR	NR
SHR	1.9:1	0.8:1	1.3:1	0.53:1	0.06:1	2.2:1	0.6:1	1.7:1

A magnetic tracking device (Polhemus 3space®) was used to evaluate GH/ST joint contribution to arm elevation in the scapular plane in 16 children with OBPP compared with non-involved limb (Duff et al., 2007). The affected limbs were divided into group 1 (≤75º arm elevation) or group 2 (>75º arm elevation) and were then compared with the non-involved side. Similar to Russo et al. (2014), the GH joint contribution was lower than ST joint ($p < 0.05$), the degree of which being directly related to severity of involvement. More ST external rotation (retraction) ($p < 0.05$) and upward rotation (lateral rotation) ($p < 0.05$) but not ST A/P tilt were found during arm elevation in the involved limbs. Duff et al. (2007) concluded that relative contributions from GH and ST joints depended on the amount of arm elevation available with greater contribution from the ST joint in the more affected arms. For those limbs capable of achieving 135º elevation the SHR (1.7:1) was not significantly different to non-involved limb (2:1) while the more affected limbs of group 1 were significantly different (0.6:1: $p = 0.05$) (Table 5.9). The current research did not distinguish the groups into more or less affected but still found a difference between groups with a SHR in the Abduction Task of 0.8:1 in children with OBPP and 1.9:1 in TDC (Table 5.9). The significant difference between groups was both in TH/GH elevation ROM (OBPP 70.96º; TDC 123.11º; $p < 0.001$ and OBPP 37.33º; TDC 81.3º; $p < 0.001$ respectively) and PTA (OBPP -98.99º; TDC -134.48º; $p = 0.002$ and OBPP -66.68º; TDC -94.77º; $p = .03$ respectively) with no significant difference in ST M/L rotation (OBPP 43.36º; TDC 43.55º; $p = 0.98$ for ROM; OBPP -

37.39; TDC -39.98; p = 0.68 for PTA). This supported the conclusion that reduced GH motion was the source of altered SHR in children with OBPP not increased ST motion.

Although SHR in children with OBPP was decreased in comparison to unaffected limbs in all studies, the influence of elevation plane on the actual ratio should be considered. The relative effect of the POE on SHR in healthy adults during arm elevation was examined by Giphart et al. (2013) using a dynamic biplane fluoroscopy system. Biplane fluoroscopy, which allows real time imaging to examine dynamic processes, has been found to measure dynamic GH joint motion to within fractions of a millimetre (Bey et al., 2006). While it can provide highly accurate kinematics of the humerus it has limited clinical application due to expense and radiation exposure. Full GH elevation in three elevation planes; frontal (abduction); scaption (30º/40º anterior to frontal plane) and sagittal (forward flexion) was analysed. They found that GH contribution to arm elevation decreased as the POE moved anteriorly from the frontal plane (Table 5.10).

Table 5.10: Scapulohumeral rhythm, arm elevation plane and glenohumeral internal rotation during elevation in three planes in healthy adults

SHR – Scapulohumeral rhythm

Adapted from Giphart et al. (2013)

	SHR	**Plane of Elevation**	**Internal rotation**
Frontal (Abduction)	2.0±.04:1	16.8º ±7.9º	19.5º ± 9.1º
Scapular (Scaption)	1.6±0.5:1	30.1º ± 8.2º	19.0º ±11.9º
Sagittal (Forward flexion)	1.1±0.3:1	81.2º ±14.7º	37.2º ± 15.0º

This means that in forward flexion, scapular motion had a greater contribution via lateral rotation to overall arm elevation compared to either scaption or abduction. In addition, at higher levels of arm elevation, (>120º) all three planes converged towards the scapular POE with more internal rotation, the largest degree of which was seen during the forward flexion task (Table 5.10). It has been found that maximum arm elevation was achieved in a plane anterior to the scapular plane with increased GH joint external rotation (An et al., 1991). This helps explain the difference between rotation in the scapular and forward flexion tasks found during the Giphart study. The results of this research study found that, at PTA in the Abduction Task, both groups had drifted towards the scapular POE (TDC: 54.12 º ±13.57 and OBPP: 45.24º ± 26.69º) (Figure 5.2). This tendency was also noted by Magermans et al. (2005) who found that at end point the TH joint was in 55º±16.6º POE. Therefore, while plane of elevation influences SHR as both groups approached the scapular plane at PTA it remains that the reduced GH joint motion in children with OBPP is the main contributor to reduced SHR.

This study has contributed further evidence that impaired GH motion is the primary reason for reduced functional ability in children with OBPP. The altered GH joint biomechanics seen in children with OBPP from an early age (Waters et al., 1998, Kozin, 2004, El-Gammal et al., 2006) and reduced active control of the GH joint, if not managed effectively, contribute to reduced function in later life. The findings of this research emphasise the importance of maintaining GH joint integrity and increasing active control where possible as the child grows. Suggestions of how to achieve this are beyond the scope of this research. While studies have examined the role of secondary soft tissue surgery (Louden et al., 2013) and bony surgery (Poyhia et al., 2011) in managing GH joint deformity there is no definitive consensus as to the most effective or appropriate procedure. Further evidence supporting the role of GH joint in impaired function validates the impetus to explore possible solutions.

5.10.3.2 Internal rotation posture

As observed clinically and in previous studies (Poyhia et al., 2005, Abzug et al., 2010, Sibinski et al., 2012, Chomiak et al., 2014) lack of external rotation, both active and passive, was a problem for children with OBPP. This was characterised in this research by a posture of internal rotation evident in all tasks of the affected group (Figures 5.2-5.7). This postural orientation would doubtlessly impact on ROM, PTA and ability to adequately perform tasks.

However, the Internal Rotation Task highlighted that despite an internal rotation posture, children with OBPP do not necessarily have good active control of internal rotation. They demonstrated significantly reduced GH AR ROM (OBPP 26.54º; TDC 76.67º; $p < 0.001$) this difference exceeded the SEM 7.1º as per Chapter 4 Reliability Results: Section 4.5.4. While significantly altered ST joint ROM was noted in all three rotation axes, the ST joint was found to have poor reliability in this research. No SEM was reported in ST P/R due a negative Cronbach's alpha. However, it is interesting to note that the differences in ST M/L rotation and ST A/P tilt in the kinematic study exceeded the SEM of 3º and 2º respectively as per Chapter 4 Reliability Results: Section 4.5.4.

The findings of this research contrasted with those of Russo et al. (2014) who found no significant difference at PTA in any axis of the ST joint. Conversely, ST M/L rotation at PTA was significantly different in this research (OBPP 12.11º; TDC -0.11º; $p = 0.003$) suggesting an altered alignment of the scapula may have compensated for reduced GH joint motion. Neither thorax nor wrist motion were analysed in this research. However, it has been commented in the literature that good wrist flexion aids reaching midline reducing the need for internal rotation (Hultgren et al., 2014).

The significant reduction in TH/GH joint internal rotation ROM observed in this research may help explain functional deficits into internal rotation after surgical interventions that aim to increase external rotation function (Abzug et al., 2010, Sibinski et al., 2012, Hultgren et al., 2014). A study examining the relationship between rotator cuff muscles and GH joint deformity using MRI found a correlation between subscapularis atrophy and external rotation contracture with greater atrophy in muscles that had been operated on (Poyhia et al., 2005). This may help to explain the poor functional ability into active internal rotation observed in this research.

The ability to examine the magnitude of pure GH joint active internal rotation is valuable in guiding which children would be more suitable for surgical intervention. Conflicting reliability results were recorded for this rotation axis. Acceptable reliability was found for ROM of GH AR (ICC 0.86; SEM 7.1º) while PTA was unacceptable (ICC 0.32; SEM 20.9º) as per Chapter 4 Reliability Results: Section 4.5.4). Therefore, while this research confirmed the clinical observation of postural internal rotation alongside reduced ROM, further investigation of the model's reliability is necessary before it can be implemented as an objective outcome measure for this rotation.

5.10.3.3 Trumpet Posture

The "trumpet posture" is a recognised pattern of movement adopted by children with OBPP to achieve the Hand-to-Mouth Task. This strategy is clinically characterised by increased TH elevation in the frontal plane, the severity of the deformity denoted by the degree of elevation (Abzug et al., 2010, Russo et al., 2014). Kinematic analysis of children with OBPP in this research clearly demonstrated these altered movement strategies during the Hand-to-Mouth Task. Significant differences at PTA in all rotation axes of the TH joint and in GH POE and AR were observed (Table 5.5). However, a significant difference in ROM was not found in either TH/GH joints. An already altered start position may have influenced ROM required or it was possible that a similar ROM was used but in different directions resulting in altered postural alignment at PTA. The altered strategy was evident from Figure 5.5.

This strategy compensated for two common deficits in children with OBPP: elbow flexion weakness and poor active GH external rotation. Elbow flexion was identified as the most important motion in Hand-to-Mouth Task (Magermans et al., 2005). Elevating the arm permits gravity assisted elbow flexion enabling the participant reach their mouth in the presence of weakness. The lack of GH joint external rotation compromised the ability to reach the mouth. This further supports the impact of reduced GH joint motion on functional ability in children with OBPP. Long term follow-up of subscapularis elongation found that it allowed effective correction of trumpet posture (Hultgren et al., 2014). Measurement of characteristic TH/GH elevation closer to the coronal plane was found to be reliable at end point suggesting that 3D-ULMA could objectively measure change in this feature pre/post intervention.

5.10.4 Scapulothoracic joint

Scapular dyskinesis is a feature commonly commented on by parents and addressed by therapists in children with OBPP (Pearl, 2009, Hale et al., 2010). Previous kinematic studies have identified alterations in the ST/GH joint couple during the performance of functional tasks (Duff et al., 2007, Russo et al., 2014, Russo et al., 2015). This research identified excessive ST motion in two tasks, Hand-to-Mouth and Internal Rotation, in children with OBPP. While scapular postural alignment was not found to be significantly different in all tasks and rotation axes visual observation of graphs highlighted an altered alignment. This concurred both with the altered alignment described by Nath et al. (2007) as SHEAR deformity and with previously reported ST kinematics in Russo et al. (2014). Conflicting opinions have been reported in the literature regarding the cause of altered scapular position and motion observed in children with OBPP. While Nath proposed that scapular deformity was the primary pathology, the general consensus was that it was a compensatory strategy for GH joint deformity, in particular GH joint abduction (Waters et al., 1998, Eismann et al., 2015) and internal rotation contracture (Waters et al., 1998, Pearl et al., 2006, Pearl, 2009).

Scapular winging, increased scapular internal rotation, during functional tasks e.g. Hand-to-Mouth was considered compensatory for reduced GH horizontal motion (Abzug et al., 2010). Measurement of GH joint abduction contracture in children with OBPP has proved challenging for clinicians. Two recent studies examined its presence in children with OBPP using MRI and 3D-ULMA to better understand its impact on function (Russo et al., 2015, Eismann et al., 2015). GH joint abduction contracture was assessed using MRI by measuring the angle of the scapular spine and the humeral shaft once full GH adduction was achieved in the affected limb and comparing it with the unaffected limb (Eismann et al., 2015). They found 25/28 participants had a GH joint abduction contracture of mean 33º ± 13º (range 10º - 65º). This correlated with increased scapular internal rotation, abductor muscle atrophy, greater Mallet abduction and Hand-to-Neck scores. This suggested that the contracture in addition to excessive ST joint motion aided functional performance especially for overhead function. In this research while there was a significant difference in TH/GH elevation ROM in both the Abduction and Hand-to-Neck Tasks, no significant difference in ST joint motion was found. It has been reported that scapular posture does not alter with <30º of GH abduction (Eismann et al. 2015). For both the Abduction and Hand-to-Neck Tasks in this research, GH elevation ROM was just over 30º (37.33º and 39.63º respectively) but ST M/L rotation was similar in both groups (TDC 43.55º; OBPP 43.36º for Abduction Task; TDC 34.55º; OBPP 42.89º for Hand-to-Neck Task) . ST M/L rotation ROM was similar in both groups despite significantly reduced GH ROM in the affected group suggesting that timing of ST motion contributed to the difference observed in ST motion during Abduction and Hand-to-Neck Tasks in children with OBPP rather than total ROM or discrete angles at PTA. However, timing of ST motion was not assessed in this research therefore it is not possible to confirm this theory. GH joint abduction contracture was not assessed in this research but its presence may have contributed to reduced ROM due to the altered start point. In future studies clinical assessment of active and passive ROM and contractures using goniometry in addition to timing of motion would aid in interpretation of kinematic data.

The contribution of a cross body abduction contracture to the presence of scapular winging was examined in Russo et al. (2015) by quantifying GH/ST contributions to cross body adduction in OBPP at PTA of the Hand-to-Mouth Task in both affected and unaffected limbs of 16 participants with OBPP using 3D motion capture system (Motion Analysis Corporation, Santa Rosa, CA). As neither ST nor GH cross-body adduction angles can be measured with an output that is consistent with clinical observations (Euler rotation sequences or helical angles) Russo defined these angles using planar projection. ST cross-body adduction was defined as rotation of the scapula about the thoracic superior/inferior axis in the thoracic transverse plane. If the scapula was aligned with the thoracic transverse plane the angle was 0º, the more anterior it was then the larger the adduction angle. GH cross-body adduction was defined as rotation of the long axis of the humerus about the superior/inferior axis (medial border) of the scapula. The cross-body adduction angle was 0º when the humerus was abducted in the scapular plane, when anterior to the scapular plane the cross-body adduction angle was larger and when posterior the angle was smaller or alternatively described as a position of cross-body abduction.

They found a significant difference in ST and GH cross-body adduction angles ($p = 0.00003$ and $p = 0.001$, respectively) between affected and unaffected sides. The GH joint contributed a negligible amount of motion to the task on the affected side compared with >50% of total motion on unaffected side. Five participants demonstrated a GH cross-body abduction position which suggested that in these cases all cross-body adduction came from the ST joint. They proposed that this position of scapular winging observed in children with OBPP was an adaptive response to decreased GH joint cross-body adduction. This study could not define the aetiology of the altered movement pattern; however it provided a description of ST and GH joint contributions to this task and aids clinicians' understanding of the pattern of scapular winging.

While these results cannot be directly compared with this study, it was found that the affected group had significantly increased (16.06º) ST M/L rotation and ST A/P tilt (10.47º) compared with TDC when performing the Hand-to-Mouth Task. Both these variables exceeded the SEM of <3.3º as per Chapter 4 Reliability Results: Section 4.5.5. These results concurred with Russo et al., (2014) who examined static differences at PTA in each of the modified Mallet positions in children with OBPP, finding that they were significantly more laterally rotated and anteriorly tilted compared with TDC on completion of this task. The findings of both studies suggested that increased ST motion compensated for reduced GH joint motion. The exact reason for this altered motion cannot be fully determined by these research studies. However, as already discussed in Section 5.10.3.3, the less GH externally rotated position at PTA (OBPP 48.68º; TDC -91.85º), in addition to reduced elbow supination ROM (OBPP 44.53º; TDC 66.89º) compromised the ability of the hand to reach the mouth. This habitual trumpet posture allowed successful completion of the task in the absence of GH external rotation and elbow supination but with increased ST motion.

Interestingly, increased ST motion was not seen in all modified Mallet positions. While agreement with Russo et al. (2014) was evident for the Hand-to-Mouth Task contrasting results were found for the Internal and External Rotation Tasks. The Internal Rotation Task has already been discussed in Section 5.10.3.2. For the External Rotation Task significant differences at PTA in ST M/L rotation ($p = 0.028$) and A/P tilt ($p = 0.001$) but not in ST P/R were found in Russo et al. (2014). Conflicting results were found in this study where only ST P/R at PTA in the External Rotation Task was significant (OBPP 31.05º; TDC 17.67º; $p = 0.02$). ST P/R was found to have poor reliability in this study. However, the difference between groups exceeded the SEM of 6.7º as per Chapter 4 Reliability Results: Section 4.5.3 suggesting this was a real difference. The capacity of the upper limb to compensate for functional deficits in a variety of ways challenges the understanding of the mechanisms of upper limb function and the implementation of repeatable upper limb motion analysis.

5.10.5 Elbow joint

Kinematics of the elbow joint were analysed in only three tasks of this study: Hand- to-Mouth; Hand- to-Neck; Hand-to-Spine. No significant difference in elbow F/E was observed but elbow P/S was significantly different in all tasks with much less supination observed compared with TDC (OBPP ROM 27.31º to 44.53º; TDC ROM 60.1º to 91.03º). Varying reports of increased and decreased elbow motion were recorded in previous studies. In a similar study, elbow flexion demonstrated a reduced arc of motion (22º versus 31º in TDC) although the kinematic curve was displaced more towards flexion during both tasks analysed; hand to mouth and moving an object across the table (Fitoussi et al., 2009). In Mosqueda et al. (2004) high reach was the only task with larger range of elbow flexion observed in children with OBPP. This study did not find a significant difference in elbow flexion in the tasks analysed suggesting sufficient ROM and active control in this sample. Consistent with OBPP presentation supination was significantly reduced in all tasks compared to TDC.

5.10.6 Increased variability in children with OBPP

The variety of possible movement combinations and inherent variability in upper limb task performance has been acknowledged in the literature. TDC have demonstrated a larger variation at the start and during task performance compared with PTA (Petuskey et al., 2007, Butler et al., 2010). It has also been identified that upper limb function continues to mature as a child grows (Schneiberg et al., 2002, Coluccini et al., 2007). In children with impaired function, such as OBPP, attempts to compensate for weakness, joint deformity and contracture may further complicate variability in task performance. It was evident in this research that children with OBPP were more varied in how individual joints contributed to task completion.

Suggested reasons for this variation included large degrees of freedom in joints, age, maturity, severity of involvement and recruitment of different strategies within the same participant as successful task completion was not always consistent. Significant differences between age groups in TDC were found for each task examined by Petuskey et al. (2007). Although, it is worth noting that no difference was >10º, with the exception of arm pronation in high reach task where a difference of 25º between 5-8years and 9-12 years was seen.

Each joint and rotation axis demonstrated variability in task performance evident both by wide SD and on qualitative analysis of graphical presentation. In general, children with OBPP exhibited wider SD compared with TDC in this research. For example the SD of the TH joint in all rotation axes of children with OBPP was twice that of TDC in the

Abduction Task (Table 5.2) and nearly three times greater in the Hand-to-Neck Task (Table 5.6). This highlighted the difficulty children with OBPP had moving their arm into a pure frontal plane position. Similar TH elevation was required to achieve the Hand-to-Neck Task but the children were permitted to adopt their preferred and most effective TH orientation within the POE. Based on clinical experience children with OBPP were more proficient at elevating their arm in the scapular plane. This was borne out by their ability to achieve 10º more elevation in the functional Hand-to-Neck Task compared with the Abduction Task which demanded elevation within the coronal plane. GH joint variability was similar to the TH joint in that children with OBPP demonstrated wider SD in all rotation axes compared with TDC (Tables 5.2-5.7). Greater variability of ST joint postural alignment was evident in the affected population. This was especially evident in ST M/L rotation and ST A/P tilt throughout task performance while ST P/R was found to be equally variable in both groups (Figures 5.2-5.7).

While this variability renders objective assessment with 3D motion analysis challenging, it permits greater potential for function in affected populations as it allows more effective compensation strategies. As all ranges of severity and a wide age span were examined in this research, future study examining the impact of severity on variability in task performance is warranted.

5.10.7 Altered start point

Efforts were made to standardise the start point by instructing the participant to place the tested arm palm down on ipsilateral knee. The challenge this presented to children with OBPP was evident from the wider variation in the start point across all joints, tasks and rotation axes (Figures 5.2-5.7). While statistical analysis of the start point was beyond the scope of this research, visual analysis of graphical output for each task permitted some comment on this variable and its contribution to research findings. An altered start point may have contributed to the inconsistency seen between significantly different variables at PTA and ROM. The larger variation most likely reflected the heterogeneity of the OBPP group and the various compensatory strategies adopted by children with OBPP to achieve the standardised start point to the best of their ability.

In general, the start point of the ST joint had the greatest variability in both groups with the exception of two tasks; Hand-to-Neck and Abduction. While it was not possible to determine the source of this variability from this research a number of factors may have influenced it: postural thorax alignment, proximal compensatory strategies for distal movement deficits, existing contracture and deformity. On observation of the graphs the trend for scapular position was coincident with the reported SHEAR deformity (Nath et al., 2007). This was described as scapula hypoplasia, elevation and rotation and was most clearly viewed in the Internal Rotation Task wherein the affected group's scapula was biased towards protraction, medial rotation and anterior tilt (Figure 5.4). However, this posture was not consistent suggesting ability to alter scapular alignment depending on task demands. In the Abduction and Hand-to-Neck Tasks scapular postural alignment was much closer to that of TDC (Figure 5.2 and 5.6).

The Abduction Task's defined start point was with the arm by the side of the thorax. It was the only task where TDC had a wider variation in start point, namely in GH POE (Figure 5.2). This was due to the initiation of elevation at varying angles within the POE. It contributed to significantly larger ROM observed compared with the affected group (Table 5.2). While this emphasised the need for standardisation in task performance in particular at start point, it has been highlighted that this particular plane proves very challenging to reference (Vanezis et al., 2015).

5.10.8 Clinical Implications

Identifying the most effective management of any condition that negatively impacts on an individual's function is the ultimate aim of any health professional. Improved functional ability and reduction in pain are the main categories of expected improvement for adolescents and their parents after any treatment for OBPP (Squitieri et al., 2013). Function was identified by parents and children in this research as the main priority

(Chapter 4 Reliability Results: Section 4.4). The following paragraphs summarise how this research can positively impact on the clinical management of children with OBPP.

As consistent significant differences in ST joint motion were not noted in all tasks, the hypothesis that each task would demand increased ST joint motion was rejected. However, this may be explained by task demands in that certain tasks e.g. Abduction/Hand-to-Neck Tasks required maximum ST joint ROM for completion, meaning children with OBPP could not avail of further ST joint motion to augment upper limb function. In this situation, while not examined in this research, timing of ST joint motion may explain scapular dyskinesia clinically observed. In contrast, for tasks that required minimal ST joint motion e.g. Hand-to-Mouth and Internal Rotation, children with OBPP were observed to move significantly more in all rotation axes of the ST joint, exceeding the SEM found in the reliability study (Chapter 4 Reliability Results: Section 4.5.4 and 4.5.5). In the absence of GH motion children should be allowed to use these compensatory strategies. However, early intervention may assist in minimising GH joint dysfunction and failing that, education with regard to improving the resting alignment of the scapula is important.

The GH joint demonstrated consistently reduced excursion in all the modified Mallet tasks suggesting that it was the main source of reduced function in children with OBPP. This agrees with previous findings by (Duff et al., 2007) and Russo et al. (2014). It has direct implications for the clinical management of children with OBPP and supports the general consensus in the literature that management of GH joint deformity and internal rotation contracture is essential to promote effective function of the upper limb. Several studies have examined the potential causes of GH joint deformity and concluded that the combined effect of impaired muscle growth and the imbalance of muscle strength contribute (Cheng et al., 2015), as do the altered net forces across the joint due to persistent internally rotated posture (Kleiber et al., 2013). Early intervention of stretches, mobilisations and facilitation of normal movement patterns to promote maintenance of joint ROM and active muscle recovery either through spontaneous recovery or post tendon transfer are important (Gharbaoui et al., 2015). This research supported the impact of GH joint on functional ability and as GH subluxation and glenoid dysplasia develop within the first year of life (van der Sluijs et al., 2001, Hale et al., 2010), early intervention is crucial.

This research did not propose to evaluate differences in the management of children with OBPP. However, a post-hoc analysis of the Abduction Task performance by the operated and non-operated participants was applied. Four participants had either subscapularis release in isolation or combined with latissimus dorsi and teres major transfers while seven had no secondary musculoskeletal surgical intervention. The operated group achieved nearly twice as much TH/GH/ST elevation in the Abduction Task but only slightly more external rotation. No consensus as to which surgical procedure was most effective in managing the secondary deformities in children with OBPP has been reached in the literature, however it is accepted that surgical intervention to address secondary musculoskeletal complications e.g. internal rotation contracture, GH joint deformity can improve functional ability (Waters and Bae, 2006, Vekris et al., 2008, Abzug et al., 2010, Poyhia et al., 2011, Sibinski et al., 2012, Assuncao et al., 2013, Louden et al., 2013). This post-hoc analysis does not represent function after surgery. However, it suggested that if patients were appropriately selected surgery may improve functional ability. Two of the participants, who were less affected, achieved equivalent ROM to the operated group indicating that surgery was not appropriate for all. Caution is advised in interpreting the above analysis as the study was not powered to analyse this data but the trend is interesting and warrants further investigation in future studies.

5.10.9 Recommended task set for 3DULMA in OBPP

It was apparent from analysing the graphs that consistent kinematic patterns were dominant across all tasks of the modified Mallet scale. This highlighted that it was not necessary to analyse all tasks. Identifying which are most appropriate to include in a 3D-ULMA task set should be evaluated based on the three criteria: task reliability; tasks that provide most information on the limitations of children with OBPP; tasks that are most functionally relevant to the population.

Considering these criteria, the three tasks recommended by this study are the Abduction, Hand-to-Spine and Hand-to Mouth Tasks. All three were found to be the most reliable. They provided information on movement of the GH joint in all planes with humeral elevation mainly examined in Abduction and humeral extension in the Hand-to-Spine Task. Despite identification of the clinically observed internally rotated position of the GH joint in children with OBPP, humeral axial rotation was not found to have sufficient reliability in this study. As external rotation movement is consistently affected in all children with OBPP, regardless of severity of involvement, further development of the model’s ability to track this motion is necessary for clinical implementation.

The movements of elbow flexion/extension and pronation/supination can also be limited in children with OBPP and were examined in the Hand-to-Mouth Task. However, the reliability of both these rotation axes needs to be improved before clinical application. The Hand-to-Mouth Task reliably characterised the compensatory pattern of “trumpet posture” in children with OBPP which surgical interventions aim to improve. Therefore, its use in any task set would aid in evaluating surgical outcomes.

Finally, while the three tasks do not address all aspects of functional demands they provide valuable information on the proficiency of children with OBPP in completing ADLs e.g. feeding/dressing/toileting.

Based on the findings of this research these are the recommended tasks to include in a 3D-ULMA protocol. It would be desirable to include a task that more specifically assesses humeral rotation but the reliability of current 3D-ULMA models to measure this is poor. Further work on developing the current models is necessary.

5.10.10 Limitations

This research aimed to characterise kinematic differences between TDC and children with OBPP while performing functional tasks. The interpretation of the results needs to be considered in the context of certain limitations outlined in the following paragraphs.

Firstly, the sample population had a range of severity of OBPP ranging from NC I-III. Potential participants with OBPP were identified from the database of the national centre for management of children with OBPP in Ireland. Insufficient numbers of each NC grade, a limit on the data collection window and the requirement of attending twice within a short time frame meant that obtaining ten of each NC grade was not feasible. Significant differences in ST/GH contributions have been found between milder and more severely affected children with OBPP (Duff et al., 2007, Russo et al., 2014). Therefore, the relative heterogeneity of the sample population influenced interpretation of the results. It contributed to the wider SD observed in children with OBPP which highlighted the variability of the sample but also directly influenced the mean angle of both ROM and PTA. In addition to classification differences, a variety of treatment histories were seen in the sample population which would have influenced kinematic findings.

Secondly, there was a wide age range (6-15 years) in the sample population. TDC were age matched to eliminate possible age related differences. However, maturation of upper limb movement characteristics may have influenced variability. There were no studies directly examining the impact of age on upper limb kinematics in children with OBPP with limited studies on the maturation of joint kinematics in TDC (Petuskey et al., 2007, Butler et al., 2010). Therefore considering both these limitations, future studies should include sufficient numbers to permit subgrouping according to both severity and age.

Thirdly, efforts were made to standardise both start point (children sat free on a bench with hips and knees at 90º, tested hand resting palm down on ipsilateral knee) and task performance with standard verbal instructions and visual task demonstration. However, the potential available combination of upper limb movement and capability to compensate with thorax and neck movement contributed to variability and large SD observed. The rationale for not implementing a more rigid start point was influenced by the wide range of involvement of children with OBPP and inability of some to achieve a rigidly defined posture. In addition, task performance mimicked clinical use of the modified Mallet scale. The ability to characterise specific joint contributions to each task of this scale was one of the aims of this research. Strict standards may limit compensatory strategies or restrict achievement of start position for all participants and therefore were not implemented. By permitting compensatory strategies this impacted on the variability seen across both groups and resulted in wide SD which due to the small sample size had a large impact on interpretation. In future studies providing a realistic but more standardised start position will reduce some of the inherent variability observed in this research.

Fourthly, although the study was statistically powered to detect a difference in TH joint external rotation between TDC and children with OBPP, the sample size of 11 was vulnerable to the different ROM possible at each joint. This may have contributed to non-significant findings in movements or rotation axes with smaller potential ROM. Future studies can be appropriately powered using reliable, significant kinematic findings of this research.

Fifthly, neither passive range of motion nor muscle strength was assessed in this research. This limits interpretation of kinematic findings.

Finally, current literature acknowledges limitations of skin fixed methods of dynamic scapular tracking in measuring upper limb kinematics (Lempereur et al., 2014). In addition, the atypical anatomical alignment of the scapula and GH joint deformity observed in children with OBPP may further compromise the ability to replicate human movement in this cohort (Nicholson et al., 2014). The complexity of defining the GH joint centre using external markers renders measurement of GH joint kinematics difficult. GH joint centre was estimated from scapular landmarks by means of regression analysis as recommended by the ISB (Wu et al., 2005). This method is limited as it uses adult anthropometric data and is based on normal anatomical alignment (Meskers et al., 1998a). Therefore, as this research had a paediatric population with atypical anatomical alignment of the scapula, accurate definition of the GH joint was compromised. Functional definition of the GH joint, while not investigated specifically in children with OBPP, has not proven to be more reliable in kinematic measurement of upper limb function in TDC (Vanezis et al., 2015). In the absence of a superior method the ISB recommendations were used. While the variable reliability of 3D-ULMA identified in this population highlighted the challenges, its quantification permitted more informed interpretation of the kinematic findings. While constantly improving 3D-ULMA needs further refinement before it can be implemented in clinical practice to inform surgical decisions.

All limitations have been considered in the interpretation of all data collected and any conclusions are within their context.

5.11 Conclusion

This chapter concludes that 3D-ULMA, using the AM of scapular tracking, can characterise kinematic differences between children with OBPP and TDC while performing functional tasks. It was concluded that reduced motion of the GH joint was the main contributor to reduced function in children with OBPP. Altered ST joint posture and motion was observed in tasks that typically demanded little ST joint motion. This was considered to be a compensatory strategy for reduced GH joint motion in particular, external rotation. It was also found that 3D-ULMA captured the internal rotation posture characteristic of children with OBPP. Furthermore reduced active control of internal rotation was also highlighted in children with OBPP. At the elbow joint a significant reduction in supination movement was found which concurred with previous research and clinical observations. Future studies of kinematics in children with OBPP should subgroup them according to age and severity of involvement; examine timing of ST joint motion and include kinematic analysis of the thorax and neck motion.

Chapter 6 Conclusions and implications

6.1 Introduction

The aims of this research were 1) to examine the test-retest reliability of 3D-ULMA during dynamic functional task performance in children with OBPP and 2) to evaluate characteristic kinematic differences between TDC and children with OBPP. There were two novel aspects to this research. Firstly, reliability of 3D-ULMA had not previously been examined in this population. Secondly, 3D kinematic comparison of dynamic task performance of children with OBPP to TDC had not been conducted. The following sections summarise this research's contributions to current literature, implications for clinical practice and makes recommendations for future study.

6.2 Contributions of the research study

6.2.1 Reliability of 3D-ULMA during dynamic functional task performance in children with OBPP

The overall findings of this research were that 3D-ULMA using the AM of scapular tracking had variable reliability. In general, sagittal plane movements were largely reliable. These movements were TH/GH elevation, ST M/L rotation and elbow F/E. Additionally the Abduction and Hand-to-Spine Tasks, whose prime movement was predominantly in one plane, were the most reliable. The External Rotation Task had the poorest reliability.

6.2.2 Contribution to existing knowledge of kinematic differences between TDC and children with OBPP

Significant differences measured between the two cohorts, in general concurred with previous research (Duff et al., 2007, Russo et al., 2014). Altered and reduced GH motion was the main source of significant differences in all tasks, particularly in the two axes POE and AR. The characteristic feature of the “trumpet posture” during the Hand-to-Mouth

Task was reliably measured and significantly different from TDC. In addition, postural internal rotation was a consistent feature captured in all tasks. The External Rotation and Hand-to-Spine Tasks had the most significant differences in the TH/GH joints for both PTA and ROM. With the exception of the Internal Rotation and Hand-to-Mouth Tasks, ROM and PTA of ST joint motion was not significantly different in children with OBPP. It was proposed that for the two significantly different tasks the increased motion facilitated task completion in the absence of GH joint motion. Elbow pronation was significantly reduced in all three tasks analysed but if had poor reliability with only the differences in Hand-to-Neck and Hand-to-Spine Tasks exceeding the SEM recorded. The significant findings of the variables, PTA and ROM, were inconsistent. This may be explained by either altered start points, variable movement patterns to achieve a similar end point or poor ability of the 3D upper limb model to track dynamic joint motion.

6.3 Implications for clinical practice and future research

6.3.1 Integrity of the glenohumeral joint

In clinical practice, children with OBPP are observed to function primarily in the scapular plane with an internally rotated posture. This observation was supported by the kinematic findings of this research with GH joint motion found to have more significant differences than ST joint motion. The impact of incomplete nerve recovery on the structure and function of the GH joint has been well documented in the literature with structural changes noted in the first year of life (Waters et al., 1998, van der Sluijs et al., 2001, Kozin, 2004, Hale et al., 2010, Cheng et al., 2015). The kinematic findings of this research supported the importance of surgical and therapeutic interventions to maintain GH joint integrity as much as possible. These should aim to maintain passive ROM and restore functional mobility. It has been noted that abduction and external rotation are not natural movements of the infant but are both learned and dependent on stability of the GH joint through the rotator cuff muscles (Gharbaoui et al., 2015). Both movements are commonly affected post

OBPP. Efforts to restore these movements through microsurgery where indicated and early therapeutic intervention focused on maintaining passive ROM and facilitating typical movement patterns are crucial. This challenge needs to be embraced by clinicians with early education of parents in their role in facilitating as much active recovery as possible in their child.

6.3.2 Scapulothoracic motion in children with OBPP

Asymmetric and abnormal scapular movement is a frequent concern in OBPP both for parents and clinicians (Hale et al., 2010) and excessive ST joint motion has been reported in the literature (Russo et al., 2014). Function was the main concern of both parent and child in this research as identified by the questionnaire outlined in Chapter 4 Reliability Results: Section 4.3. The conclusion from these research findings was that the ability of the ST joint to compensate for lack of GH joint motion was task dependent. For the two tasks that required a large degree of TH elevation, Abduction and Hand-to-Neck Tasks, there were no significant differences in ST motion between the two groups. This may be explained by the fact that these tasks demanded maximum ST motion from both groups. Consequently the ST joint in children with OBPP had no more to offer in terms of compensatory strategies. It was noted in the literature that altered ST motion may persist even in the presence of returned GH joint motion (Gharbaoui et al., 2015). This observation may be due to the development of atypical movement patterns and neural adaptations. As pure active and passive joint ROM and muscle power were not assessed in this research study it is difficult to comment if altered ST motion persisted despite active GH joint motion. The addition of a clinical ROM and muscle power assessment to the 3D-ULMA protocol would allow for greater interpretation of the kinematic findings. This is recommended for any implementation of 3D-ULMA into clinical practice.

Qualitative observation of graphical output suggested an altered scapular resting posture in children with OBPP. Its position tended to be more protracted and medially rotated. The presence of altered scapular alignment and motion highlight the necessity of re-educating children with OBPP with regard to postural alignment and coordination of ST and GH joint motion where possible. Currently, therapeutic intervention to address this includes active and passive ROM, stretching, taping, splints and botulinum toxin. While the use of botulinum toxin as an adjunct to therapy and surgery in the management of muscle imbalance, co-contraction and contractures has been explored with positive outcomes, the quality of studies has been quite poor (Gobets et al., 2010, Michaud et al., 2014). There is a lack of evidence in the literature exploring individual components of therapy programmes e.g. taping, splinting, and stretching to address movement dysfunction in OBPP. Future studies are necessary to evaluate the impact of these therapeutic intervention programmes on scapular alignment and coordination of ST and GH joint motion. While not examined in this research, timing of ST joint motion may also help explain clinically observed scapular dyskinesia and should be explored in future studies.

6.3.3 Three-dimensional upper limb motion analysis as an outcome measure in children with OBPP

This research has provided data on the reliability of 3D-ULMA to measure dynamic functional task performance of children with OBPP. It did not evaluate its ability to reliably measure change over time or before and after an intervention. Future research is necessary to answer this question.

6.3.4 Alterations in the kinematic protocol

The capacity of 3D-ULMA using the AM to reliably record kinematics in children with OBPP was found to be quite variable. Caution has been advised against introducing more individualised methods of musculoskeletal modelling over the existing generic models as their superiority has yet to be proven (Bolsterlee et al., 2013). Significant alterations to the model are beyond the scope of this research. However, suggestions are made based on the experience gained during this research that could improve the existing protocol's implementation into clinical practice.

6.3.4.1 3D upper limb model and methodology

Firstly, linear regression was used to define the GH joint in this research. As this method was based on typically developing adult shoulder alignment, there are limitations in using it with a paediatric population and one with atypical anatomical scapular alignment and GH joint deformity. Based on visual observation of the stick figure the anatomical location of the GH joint did not appear valid as it was predominantly positioned anterior to the bony landmark, processus coracoideus (coracoid process), rather than laterally. Future comparison of the reliability of functional methods to define the GH joint (Lempereur et al., 2010) in this population would contribute to the knowledge as to which is the most appropriate to use.

Secondly, motion analysis is well established for gait but upper limb analysis, with its large degrees of freedom, presents additional challenges and, therefore, may require specific technical considerations in excess of more routine gait analysis protocols. Marker view was a challenge with this protocol due to location of anatomical markers and the number of cameras permitted by the optoelectronic system. An increased number of cameras would increase the potential capture field which may address this problem for certain tasks. Additionally the integration of a technical cluster for the thorax would remove the problem experienced with anterior thorax marker view during functional task performance. Due to the orientation of the forearm, the participants' body occluded forearm markers during the Hand-to-Spine Task. Resolution of this problem is not as simple. Exploring positioning of cameras and possible use of an extra camera to enhance the potential capture field may help rectify this issue.

Thirdly, it has been recommended in the literature to combine recordings of scapular orientation by the AC and the SL both at the start and end of movement. This allows correction of possible orientation changes in the AC which may impact on reliability findings. While this adds to the length of the recording session and challenges compliance in a paediatric population, the proposed improved reliability of the recordings would enhance the effectiveness and benefits of a prolonged session. The quantification of the improvement of this method needs to be measured in this population.

The suggestions above are based on the experience and knowledge gained in completing this research study but need further exploration to evaluate their impact on reliability of 3D-ULMA in children with OBPP.

6.3.4.2 Functional task set

To ensure the clinical applicability of a motion analysis protocol, defining a task set that reflects functional deficits in children with OBPP, is feasible for a paediatric population in a clinical setting and can be reliably measured is essential. This research study contributed to this process by identifying reliable parameters that can be measured. These were mainly in the Abduction, Hand-to-Spine and Hand-to-Mouth tasks. Due to the impact of the common problem of reduced rotation control in children with OBPP and the poor reliability of the AR axis found in this research, further exploration of how the model can reliably measure AR is necessary. Furthermore, based on qualitative observation of participants' task performance future studies should include analysis of both head and thorax motion. Both these segments were observed to contribute significantly to compensatory strategies adopted. This information would enhance the knowledge of mechanisms of movement performance.

6.3.4.3 Subgroup with regard to age and severity

The sample population in this research was a heterogeneous group including a wide age spread (7-15years) and three of the four grades of the NC, missing only the severest grade. This contributed to the large SD and outliers observed and limited the interpretation of results. Future research studies could subgroup according to both NC to differentiate between levels of severity and age as upper limb control continues to mature into adulthood (Schneiberg et al., 2002, Dayanidhi et al., 2005, Coluccini et al., 2007, Petuskey et al., 2007).

6.4 Future Research

This section briefly summarises recommendations for future research:

¶ Compare the reliability of functional methods to define the GH joint (Lempereur et al., 2010) as opposed to the linear regression method used in this research (Meskers et al., 1998a). This would contribute to the knowledge as to which is the most appropriate to use in this population.

¶ Compare recordings of scapular orientation by the AC and the SL methods both at the start and end of movement to allow for correction of possible orientation changes in the AC. This may improve reliability of the model.

¶ Explore how 3D-ULMA model can reliably measure humeral AR.

¶ Subgroup participants according to NC to differentiate between levels of severity and age as upper limb control continues to mature into adulthood

¶ The addition of a clinical ROM and muscle power assessment to the 3D-ULMA protocol would allow for greater interpretation of the kinematic and reliability findings.

¶ Include analysis of both head and thorax motion in future studies as these segments were observed to contribute significantly to compensatory strategies adopted.

¶ Evaluate the impact of therapeutic intervention programmes on scapular alignment and coordination of ST and GH joint motion.

¶ Examine the timing of ST joint motion in children with OBPP. This may help explain clinically observed scapular dyskinesia.

6.5 Conclusion

This research aimed to evaluate the reliability of 3D-ULMA, using the AM, in children with OBPP and subsequently to characterise the kinematic differences during functional task performance between children with OBPP and TDC. Discrete angles at PTA and for ROM recorded were analysed both for reliability and significant differences. Additionally, graphical presentation of the kinematic waveforms permitted analysis of task performance. The 3D-ULMA model was found to have variable reliability across all joints, rotation axes and tasks. The TH joint, elevation; ST M/L rotation; elbow F/E and the Abduction and Hand-to-Spine Tasks overall had acceptable reliability. Despite variable reliability the quantification of SEM for all variables facilitated interpretation of the significant kinematic differences between children with OBPP and TDC. Significant differences between the two cohorts were identified in all six tasks analysed, particularly in the TH and GH joints. The GH joint was considered to be the main contributor to reduced functional ability, in particular, into external rotation and elevation. Significant differences in ST joint motion were not consistent across tasks. This outcome measure could reliably characterise clinically observed kinematic differences in task performance in children with OBPP with future work necessary to establish its ability to reliably measure change. This research concurred with the existing literature on the importance of maintaining the integrity and function of the GH joint as much as possible to enhance the functional ability of these children.

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Appendices

Appendix 3.1: Approval letter from the Central Remedial Clinic Scientific and Research Trust Ethics committee

Central Remedial Clinic
An Lárchlinic Feabhais

Foirgneamh Penny Ansley
Penny Ansley Building
Ascaill Vernon
Vernon Avenue
Cluain Tarbh
Clontarf
Baile Átha Cliath 3
Dublin 3
Éire
Ireland

Fón/Tel: +353 (0)1 854 2200
Facs/Fax: +353 (0)1 833 5496
Ríomhphost/Email: info@crc.ie

Ms. Judy Mahon,
Senior Physiotherapist,
Motion Analysis Laboratory,
Central Remedial Clinic.

Copy: Mr. Paul O'Donoghue, Administrator Research Trust, CRC.

19th December, 2013 OH/pe

Re: Ethics Master Proposal titled:
"3 Dimensional movement analysis of the upper limb during activities of daily living in children with obstetric Brachial Plexus Injury: comparison with healthy controls".

Dear Ms. Mahon,

Thank you for submitting the above research project for ethical consideration. I note the amendments you have made following our discussion.

Your paper has been considered for ethical approval and I am happy to confirm that the project has been approved by the Central Remedial Clinic Ethics Committee.

Yours sincerely,

O Hensey

Dr. Owen Hensey,
Medical Director.
MCRN: 05445

Appendix 3.2: Recruitment letter to Erb's Palsy Association of Ireland

Foirgneamh Penny Ansley, Penny Ansley Building

Ascaill Vernon, Vernon Avenue

Cluain Tarbh, Clontarf

Baile Atha Cliath 3, Dublin 3

Eire, Ireland

Fón/Tel: +353(0) 1 854 2200

Facs/Fax: +353(0) 1 833 5496

Ríomhphost/Email: info@crc.ie

Dear Chairperson,

I am a physiotherapist in the Central Remedial Clinic (CRC) currently on a two year rotation in the Gait Laboratory. I have started a part time masters by research through the CRC, in collaboration with Royal College of Surgeons in Ireland (RCSI).

The primary aim of this research is to establish the reliability of a three dimensional (3-D) movement analysis model in chil system has been pioneered in the analysis of walking and has contributed hugely to improving our understanding of the function and problems in the lower limb. Use of 3-D movement analysis in the upper limb has not been as extensively explored. However, it is felt that 3-D movement analysis in chi Palsy will improve our understanding of how and why they function as they do. It is the aspiration that this will lead to development of a clinical service, subject to the results of the study.

The project will recruit ten children wit -18yrs who will attend the CRC gait laboratory on two separate occasions within 48hr-2weeks of initial assessment. I will also be looking for ten age and gender matched typically developing children to Palsy. I hope to recruit participants through CRC Physiotherapy and Occupational Therapy Department and will be contacting parents in the coming weeks if they are happy to participate.

Further details of the study and assessment process are found in the attached information leaflet. I just wanted to inform your association of the ongoing research into Erbôs Palsy and on completi

present the outcome to your group if you deemed it to be of interest.

If you have any further questions please do not hesitate to contact me on 01 8542331 or jmahon@crc.ie

Regards

Judy Mahon, MISCP
Senior Physiotherapist

Appendix 3.3: Participant information leaflet

Gait Laboratory Upper Limb Study

Participant Information Leaflet

Study Title

Three dimensional movement analysis of the upper limb during activities of daily living in children with obstetric brachial plexus injury: comparison with healthy controls

Investigators

Ms. Judy Mahon, Senior Physiotherapist

Ms. Dara Meldrum, Senior Physiotherapist (Supervisor RCSI)

Dr. Ailish Malone, Senior Physiotherapist (Supervisor CRC)

Mr. Damien Kiernan, Clinical Engineer

Mr. Mike Walsh, Gait Laboratory Manager

Prof. Tim O'Brien, Consultant Orthopaedic Surgeon & Gait Laboratory Director

Contact Details

Ms. Judy Mahon, Gait Laboratory, Central Remedial Clinic, Vernon Ave, Clontarf, Dublin 3

Email: jmahon@crc.ie

Tel: 01-8542 331

Introduction

Your child is invited to take part in a clinical research study at the Gait Laboratory in the Central Remedial Clinic (CRC). Before you decide whether he or she will take part, please read the information provided below carefully and, if you wish, discuss it with your family, therapist or doctor. Take time to ask questions.

You should clearly understand the risks and benefits of taking part in this study so that you can make a decision that is right for your child. This process is known as 'Informed Consent'.

Your child does not have to take part in this study. If you decide not to take part it won't affect your child's future care at the CRC. You may change your mind at any time without having to justify your decision and without any negative impact on your child's care.

Why is this study taking place?

Despite improvements in medical management, the number of children with obstetric brachial plexus injury, also known as Erb's Palsy, has remained the same in Ireland over the past ten years. This results in the loss of the ability to use the affected arm to varying degrees. Some children have a full recovery. Those that don't are left with long lasting difficulty in using their arm in daily life. They will need ongoing treatment to get the best out of their arm. The assessments used by therapists are reliable, giving us some information on how the arm moves as a whole but little on what each joint does within that movement. Three-dimensional movement analysis involves the placement of markers, consisting of small lights, onto a particular part of the body, to allow recording of movement by a computer, which can then be examined in more detail. Its inclusion in the assessment of children with Erb's Palsy will help our understanding of their movement. This information will help healthcare professionals who work with children with Erb's Palsy to better understand and manage their difficulties.

Who is organising and funding this study?

This study is organised by the staff members of the Gait Laboratory in the CRC in conjunction with the School of Physiotherapy in the Royal College of Surgeons in Ireland (RCSI).

Why has my child been invited to take part?

Your child has been invited to take part because:

- your child has Erb's Palsy and has difficulty completing some tasks of daily life effectively.

OR

- your child has normal function in their arm and their abilities will be a valuable comparison for children with Erb's Palsy.

How will the study be carried out?

This study will be carried out in the Gait Laboratory at the CRC. Ten children with Erb's Palsy and ten typically developing (TD) unaffected children will be invited to participate. Each typically developing child will attend the Gait Laboratory for one assessment which will take about 60 minutes. Each child with Erb's Palsy will attend the gait laboratory for two assessments, which will be exactly the same. The second assessment will be completed within a period of 24hrs to 2 weeks after the first assessment at a date and time convenient for you and your child. Each assessment will be carried out by the primary researcher, Judy Mahon, and will consist of:

1. A short questionnaire about the child's abilities to be answered by the parent or by the child with parental help (for children with Erb's Palsy only)
2. Carrying out some simple functional tasks e.g bring hand to mouth/head and movements of shoulder, elbow, wrist and hand. We will grade each movement according to two established scales.

3. Placement of a group of small lights on the child's upper back and the affected arm in Erb's Palsy, and non-dominant arm in TD children. These will be placed with sticky tape and velcro straps. As the arm moves, the lights are seen by a computer which changes the movement into a stick picture of the arm, allowing us to closely examine what each joint is doing during the task.
4. The child will do the following tasks three times while wearing the markers:
    a. Lift arm out to side
    b. Bring hand away from body while elbow is held beside body
    c. Bring hand to back of neck
    d. Bring hand to lower spine
    e. Bring hand to mouth
    f. Bring hand to tummy
5. Your child will have close supervision at all times. If they become distressed or upset at any point the assessment will be stopped. They will not be asked to do any movement that causes pain and can ask to stop at any stage without any negative impact on their care.
6. With consent, a video will be taken of the assessment to ensure its quality.

What are the benefits of taking part in the study?

If your child has Erb's Palsy, the information gained from this assessment will help to measure his or her movement patterns and limitations. This will guide your child's physiotherapist in choosing the best strategies to improve function and make progress in therapy, both for your child and for children with similar problems.

Children without Erb's Palsy will not gain a direct benefit for themselves however their participation will help to provide a better care for children with Erb's Palsy who have problems completing tasks of daily life.

What are the risks of taking part in the study?

This study has minimal risks. One minor issue may be a concern:

1. The markers for the analysis system are applied with sticky tape, similar to a "Band-Aid", and your child may find them a little uncomfortable when they are removed.
2. If your child is sensitive to plasters the sticky tape may leave red marks that may take a while to go away.
3. If your child gets distressed or has any pain during the assessment we will stop immediately.

Is the study confidential?

When your child participates in the study, his or her identity and diagnosis (if any) will be known only to the research staff. Any information arising from the assessment that may help your child, for example, information on limitations in movement at a particular joint, will be shared with his or her physiotherapist only with your permission and only for the purpose of improving your child's care.

Your child's details will be linked to a confidential code, instead of their name. The code will be stored in a secure locked location within the gait laboratory and only the researcher will have access. All your child's data (information on the movement in their arm) will be stored securely on a database under that confidential code. This database is only accessible to staff in the Gait Laboratory department. Their identity (including any other identifying details, such as address or date of birth) will not be revealed to people outside the study. When the results of the study are published or presented, your child will not be identified. Instead, summaries of the results for all children with and without Erb's Palsy will be presented and compared. All sensitive data will be kept for a minimum of five years following the end of the study after which it will be destroyed.

A video of your child performing the upper limb tasks will be recorded. This is to help with the interpretation of the results afterwards. This video will be stored on a secure server, only accessible to the staff within the physiotherapy and gait laboratory departments, with a confidential code instead of your child's name to protect their identity. Videos will only be viewed by the research team and will not be released to people outside the study.

In some cases, we may request permission to present your child's video to other healthcare professionals at conferences or courses where it could be an educational benefit to these people. We will seek your permission specifically for this purpose. You have the right to decline this request with no negative impact your child's care.

Where can I get further information?

Please contact Judy Mahon, Senior Physiotherapist at jmahon@crc.ie or 01-8542331 if you have any questions.

Appendix 3.4: Recruitment letter to potential participants

Central Remedial Clinic

Foirgneamh Penny Ansley, Penny Ansley Building

Ascaill Vernon, Vernon Avenue

Cluain Tarbh, Clontarf

Baile Atha Cliath 3, Dublin 3

Eire, Ireland

Fón/Tel: +353(0) 1 854 2200

Facs/Fax: +353(0) 1 833 5496

Ríomhphost/Email: info@crc.ie

To Whom It May Concern,

Firstly, thank you for taking the time to read this information and consider taking part.

I am a physiotherapist in the Central Remedial Clinic (CRC) currently on a two year rotation in the Gait Laboratory. I am starting a part-time masters by research through the CRC, in collaboration with Royal College of Surgeons in Ireland (RCSI). The primary aim of this research is to establish the reliability of a three dimensional (3-D) movement analysis model in children with Erbôs palsy. Thi involves placing small markers with ligh computer to record its movement. This allows us then to closely examine the arm movement. This will improve our understanding of how and why they function as they do and will hopefully, in the future, provide an objective measure of arm function pre and post-surgery.

To complete the project I need ten children with Erbŝ Palsy between ages 6-18yrs who will attend the CRC gait laboratory on two separate occasions within 48hr-2weeks of initial assessment. I will also be looking for ten age and gender matched typically developing children to compare with the children with Erbŝ Palsy.

Further details of the study and assessment process are found in the attached information leaflet.

If you have any further questions please do not hesitate to contact me on 01 8542331 or jmahon@crc.ie

Yours sincerely,

Judy Mahon

Appendix 3.5: Participant consent form

Gait Laboratory Upper Limb Study

Participant Consent Form

Study title: Three dimensional movement analysis of the upper limb during activitie of daily living in children with obstetric brachial plexus injury: comparison with healthy controls

I have read and understood the Information Leaflet about this research project. The information has been fully explained to me and I have been able to ask questions, all of which have been answered to my satisfaction.	Yes	No
I understand that my child doe can opt out at any time. I understand t for opting out and I understan future care.	Yes	No
I am aware of any potential risks of this research study.	Yes	No
I have been assured that information about my child will be kept private and confidential.	Yes	No
I have been given a copy of the Information Leaflet and this completed consent form for my records.	Yes	No

Storage and future use of information:

I give my permission for information collected about my child to be used in related studies in the future but only if the research is approved by a Research Ethics Committee.	Yes	No

Special Consent for Videos:

I give my permission for my ch healthcare professionals for teaching purposes only. I understand that my child's name or other ident	Yes	No

/ K ⅄ ſ Ř Ω ἐ Parent / guardian name Parent / guardian signature Date

To be completed by the Principal Investigator or nominee.

I, the undersigned, have taken the time to fully explain to the above participant the nature and purpose of this study. I have explained the risks involved as well as the possible benefits. I have invited them to ask questions on any aspect of the study that concerned them.

Name (Block Capitals) Qualifications Signature Date

Appendix 3.6: Questionnaire

Upper Limb Questionnaire

¶ **Thank you for taking the time to complete this questionnaire.**
¶ **If you are not sure of any of the questions please just ask me to explain.**
¶ **If you don't know the answers to some questions just leave them blank.**
¶ **Parents/guardians are asked to complete the questionnaire in discussion with their child.**

1 Personal Details

a. Boy □ Girl □
b. 6yrs or younger □ 7-9yrs □ 10-12yrs □ 13-15yrs □ 16-18yrs □

2 Birth Details

a. Timing: Pre-term □ Term □ Overdue □
b. Birth weight: ____________________ (lbs or kg)
c. Delivery: Natural □ Caesarean □ Forceps □ Vacuum □

3 Surgery

a. Nerve Surgery (repair of nerve roots ~3-9mths old)
Yes □ No □
Date & Roots repaired if known:
____

b. Nerve Transfer (move nerves from one place to another)
Yes □ No □
Date & Type if known:
____

c. Muscle Release (short muscles lengthened)
Yes □ No □
Date & muscle if known:
____

d. Muscle Transfer (move muscles to improve movement)
Yes □ No □

Date, muscle & to improve what movement:

____

e. Bone Surgery Yes □ No □
Date & bone if known:

____

4 Everyday living

a. Does your child need help with everyday activities?
Yes □ No □

If yes, please select the different tasks from the list below

Tying up hair □ Washing hair □ Doing up buttons/laces □
Dressing □ Preparing Food □ Eating □
Reaching high cupboards □ Writing/school work □ Other □

Please specify:

____

5 Pain

a. Does your child have any pain? Yes □ No □

If yes,

¶ Where is the pain?

____

¶ When do they complain of pain?

____

¶ What eases the pain?

____

6 Sensation/Feeling

a. Does your child ever complain of pins and needles or numbness?

Yes □ No □

b. Does your child have difficulty feeling objects e.g. difficulty feeling bobbin in hand when tying up hair/ unsure if an object is in their hand unless looking at it?

Yes □ No □

7 Other

a. Is your child satisfied with the way they use their arm?

Yes □ No □

If no, why and what would they like to improve?

Are you and your child happy with how their arm looks?

Yes □ No □

If no, why and what would they like to change?

Thank you for taking the time to complete the questionnaire.

Appendix 3.7: Rules for data reduction

Rule 1a: Correctable Gimbal lock

Problem

- If, on visual inspection of stick figure and graph in Odin, an immediate flip of one graph to a very similar point but of reverse sign is observed, gimbal lock (GL) has occurred.

Action

- Data were visually inspected in excel, point at which lock occurred was identified by two methods - time in was noted in ODIN and the change from +ve to –ve in Excel
- By adding or subtracting either 360 or 180 from the original figure the lock was corrected.
- When the gap between data was small (<20points), a linear interpolation was applied
- If the gap was larger (>20points), area was left blank

Task	Trials Amended in Participants with OBPP
Internal Rotation	THX/Z: MUM1002_26/27/28
Hand-to-Mouth	ELBFE: PAN0101_06/07/08
	ELBPS: PAN0101_06/07/08
Hand-to-Neck	ELBFE: PAN0101_12/13/14
	ELBPS: Pan0101_12/13/14
	THX: MUM1001_17
Hand-to-Spine	TSRP: MUM1002_31
	GHZ/THX/THZ: MUM1002_29/30/31

Task	Trials Amended in TDC
Abduction	THX: FAS0202_12
External Rotation	GHX/GHZ: FAS0202_24/25
	GHX/GHZ: TAC0302_14/15
	THX: MOR0202_18
	GHZ: GEM1003_26
Internal Rotation	GHX/Z: FAS0202_27
Hand-to-Mouth	ELBPS KEC1203_6/7/8
Hand-to-Neck	ELBPS KEC1203_21/22/23

Rule 1b: Gimbal Lock pre movement

Problem

- ¶ GL occurs prior to start of actual movement

Action

- ¶ This was identified on visual inspection of graphs in ODIN/Excel.
- ¶ Lock data deleted until it reaches the trend of movement

This was not observed in participants with OBPP.

Task	Trials Amended in TDC
Abduction	THX: FAS0202_12/13/14

Rule 2: Incorrect direction of movement

Problem

- ¶ On visual inspection the ODIN graph is moving in the incorrect direction e.g. stick figure is externally rotating but the graph indicates internal rotation.
- ¶ It was determined that gimbal lock occurred when the arm crossed midline reversing the direction of movement mathematically.

Action

- ¶ Corrected by multiplying the original figure by -1 to achieve correct direction of movement
- ¶ Discarded data if unable to correct with meaning

This was not observed in participants with OBPP

Task	Trials Amended in TDC	Trials Discarded in TDC
Abduction	GHX/Z: FAS0202_13/14	
External Rotation	GHZ: TAC0302_15 THZ: KEC1203_13/14/15; GEM1003_24: ROJ0302_14: ROB0202_13/14/15; TAC0302_14/16	
Internal Rotation	THZ: GEM1003_28 THZ: FAS0202_25	
Hand-to-Neck	THX: MOR0202_15/16/18 THZ: MOR0202_15/16/18 STZ: MOR0202_15/16 STX: MOR0202_15/16	ELBPS: FAS0202_16

Rule 3: Query true movement:

Problem

- ¶ Insufficient marker view
- ¶ Technical issues on inspection in ODIN – markers jump; graph shows movement when stick figure is still; loss of stick figure joins despite report of full marker view.
- ¶ Resembles GL but it is not fixed with rule 1 - Graph moves from negative to positive over a very short space but not an immediate flip, possibly due to crosstalk. This was not correctable in Excel without loss of excessive data therefore this data was discarded.

Action

- ¶ Spikes are deleted from the data if true movement precedes or follows the spike and trial is included if sufficient data remains
- ¶ Trial discarded if insufficient data or no acceptable fix

Task	Trials Amended in participants with OBPP	Trials Discarded in participants with OBPP
Abduction	GHY:Pan0101_10 FOJ0702_10/11/12 THX: FOJ0702_10 THZ: FOJ0702_11 TSRP: FOJ0702_10/11/12 MUM1002_17 THX:MUM1002_25	GHX: PAN0101_10/11 GHZ: PAN0101_10 THX:FOJ0702_11/12 All Planes: MUM1002_16/18 WAA0801_27 – missing at start
External Rotation		All planes: MUM1002_23/25
Internal Rotation		GHX/Z/THX//Z: MUM1002_26/28 GHX/Z/THX//Z: CLE0102_24 – missed start of movement so not reflective of task GHX/THX/Z: MUM1002_27 – GL mid movement
Hand-to-Mouth	GHX/Y/Z: PAN0101_06/07/08 THX/Y/Z: CLE0102_17 STX/Y/Z: CLE0102_17	All planes: MUM1002_15
Hand-to-Neck	GHX/Y/Z: MUM1001_17 THX/Y/Z: MUM1001_16/17 STX/Y/Z MUM1001_16/17 THX: FOJ0702_14 ELBFE/PS:HUS0602_14 /15/16 GHX/Z/THX/Y/Z/STX/Y/	GHX/Z:PAN0101_14 THX: PAN0101_14 GHX/Y/Z: ODJ0302_24 GHX:UYL0101_20 THX:UYL0101_20 STX/Z: UYL0101_20 GHZ/THX/THZ: RYE0402_22 THX: MUM1001_16

Task	Trials Amended in participants with OBPP	Trials Discarded in participants with OBPP
Hand-to-Spine	Z: ELBPS: MUM1002_20/21 GHX/Z/THX/Z: PAN0102_13 – IGL GHX/Z/THX/Z/STZ PAN0102_08 GHX/Z/THX: FOJ0702_12 GHH/THZ: FOJ0702_11 THX/Y/Z STX/Y/Z: HUS0601_28/29 – ELPS/FE:FOJ0701_26 GHX/Z/THX/Z: MUM1002_20/21 amended end deleted as GL with no true end point	GHX: PAN0101_21/22/23 GHZ: PAN0102_22/23/25 GHX: PAN0102_22/23/25 THX: PAN0101_15 THZ: PAN0101_15

Task	Trials Amended in TDC	Trials Discarded in TDC
Abduction	GHZ: TAF0202_11/12/13	MOR0202_11: All planes THX: FAS0202_13/14 GHZ: FAS0202_13/14
External Rotation		GHX: TAC0302_15 THX: GEM1003_26 STY: ROB0202_14; KEC1203_14 STZ: ROB0202_13/14; TAC0302_16
Internal Rotation		STZ: FAS0202_27
Hand-to-Mouth	TSRP: MOR0202_17	THX/THZ: GEM1003_18/20 THX/THZ: FAS0202_18/19/20 GHX: FAS0202_18 GHZ: FAS0202_18/19
Hand-to-Spine		ELBFE/PS: TAC0302_26/29/30

Rule 4: Spikes

Problem

¶ On inspection of the data in Odin spikes that do not reflect true movement as observed in the stick figure and may be caused by marker occlusion, markers jumping between CODAs or unknown reason.

Action

¶ Spike is deleted from the data if true movement precedes or follows the spike and trial is included if sufficient data remains

Task	Trials Amended in participants with OBPP
Abduction	GHX: PAN0101_09 GHZ: PAN0101_09/10/11 GHY: PAN0101_10 STX/Y/Z: HUS0601_16 STZ: HUS0601_31 THX/THZ/THY:HUS0602_06/09 STX/Z: WAA0801_13 GHX/Z: FOJ0701_09/11 THX/Z: FOJ0701_09/11 GHZ: CLE0101_12 STX/Y/Z/THX/Z: CLEO0101_14/15 GHX/Z: CLE0101_9/10/11 THY: CLE0101_09 THX: CLE0101_9/10/11 THY/Z: CLE0102_12 TSRP/TSAP: CLE0102_12 THX/Y/Z & STX/Y/Z: MUM1001_19/20/21
External Rotation	THX/Z MUM1002_25/23 STX: MUM1002_23
Internal Rotation	GHX: PAN0101_18 GHZ:MUM1002_28
Hand-to-Mouth	THX/GHX: PAN0101_07; THY/Z: PAN0101_07/08 STX/Z: PAN0101_06/07/08 THY: UYL0102_08; STX/Z:UYL0102_08 GHY/Z: KID0201_07 STX/Y/Z/THX/Y/Z: HUS0602_06/09 THY: RYE0401_07; STY/Z: RYE0401_07 STX RYE0402_06/07 STX: RYE0402_22; STY:RYE0402_21/22 THX:RYE0402_06 THX/Z: CLE0102_17
Hand-to-Neck	GHX/Z: PAN0102_14 THX/Y/Z:PAN0102_14/15 STX/Y/Z: PAN0102_14/15 STX/Y/Z: HUS0601_28/29 GHZ: UYL0101_20

Task	Trials Amended in participants with OBPP
	THX/Z: FOJ0701_14
	STX/Z: FOJ0701_14
	STZ: FOJ0701_13
	GHX/Z: FOJ0701_13
	GHX: WAA0801_23
	GHX/GHZ:RYE0402_28/29
	THX/Y/Z/STX/Y/Z MUM1002_20/21
	GHX/Z: CLE0101_10/11
	THX: CLE0101_09/10/11
	GHZ: CLE0101_12
	THX/Y/Z:CLE0101_14/15
	STX/Y/Z: CLE0101_14/15
	THX/Z:CLE0102_14/15
	STX/Y/Z CLE0102_14/15
Hand-to-Spine	ELBPS:WAA0801_27/29

Task	Trials Amended in TDC
Abduction	THZ/STZ: WAE0402_9/10/11
	THZ: MOR0202_9
	THZ: TAF0302-11/12/13
External Rotation	GHY: TAC0302_16; GEM1003_24
	GHZ: TAC0302_16
Hand-to-Mouth	THY: ROJ0302_7
	THX: ROJ0302_7
	TSZ: ROJ0302_7/10
	STY: ROJ0302_7/10
	STZ: ROJ0302_10
Hand-to-Neck	THX: GEM0103_30/31/32: MOR0202_15/16
	STX: MOR0202_15/16/17; TAC0302_25
	STZ: MOR0202_15/16: WAE_20/21
	ELBPS: TAC0302_24
Hand-to-Spine	GHX: GEM1003_33
	GHZ: GEM1003_33
	ELBPS: TAF0202_09; TAC0302_26/29/30
	ELBFE: TAC0302_26/29/30

Rule 5: Other problems

Problem

- ¶ No movement recorded despite stick figure visibly moving
- ¶ Data extremely different from mean data presentation when viewed together and deemed not true movement
- ¶ Existing gap due to a deletion because of one of other rules

Action

- ¶ Trials were discarded due to significantly skewing the mean

Task	Trials Discarded in Participants with OBPP
External Rotation	STY: PAN0101_16 THY:PAN0102_18
Hand-to-Mouth	GHX/Z_PAN0102_08 THX/Z_PAN0102_08
Hand-to-Neck	ELBFE:PAN0101_14 ELBPS:PAN0101_14 GHX/Y/Z: HUS0601_24 THX/Y/Z:HUS0601_24 STX/Y/Z:HUS0601_24 All planes: UYL0102_30

Task	Trials Discarded in TDC
Abduction	THY: FAS0202_14; GEM1003_23 THZ: GEM1003_23
External Rotation	GHX: TAC0302_15 GHZ: TAC0302_15 THY: FAS0202_24 THX: ROB0202_15
Internal Rotation	THX: GEM1003_27/28/29; FAS0202_25/27 (no movement) GHX: MOR0202_21; GEM1003_27/28/29: FAS0202_25/27 (no movement) GHZ: MOR0202_21/22/23; GEM1003_27/28: FAS0202_25/27 (no movement)
Hand-to-Spine	THX: GEM1003_33/34/35; FAS0202_6/7/8 (no movement) THZ: GEM1003_33/34/35; FAS0202_6/7/8 (no movement) GHX/Z: GEM1003_33/34/35; FAS0202_6/7/8 (no movement) STX: GEM1003_33/34/35 (no movement) STZ TAC0302_29/30 (inconsistent within trials)

Appendix 3.8: Trials used for children with OBPP's average waveform

Table 1: Number of trials used to calculate mean trace for each participant's task performance for initial data exploration

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX:Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck

MUM1001/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/1	3/1	3/1	0/1	0/1	0/1	0/1	0/1	0/1		
External rotation	3/1	3/1	3/1	3/1	3/1	3/1	3/1	3/1	3/1		
Internal Rotation	3/0	3/3	3/1	3/0	3/3	3/0	3/3	3/3	3/3		
HTM	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	2/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
PAN0101/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	1/3	3/3	2/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/2	3/3	3/3	2/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/2	3/3	3/2	3/2	3/3	3/2	3/3	3/3	3/3	3/3	3/3
HTS	0/0	3/3	0/0	2/3	3/3	2/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	2	3/3	3/3	3/3	3/3	3/3	2/3	2/3

HUS0601/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	3/3	3/3
UYL0101/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**

Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/1	3/2	3/2	3/1	3/2	3/2	3/1	3/2	3/1	3/2	3/2
FOJ0701/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/1	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3

WAA0801/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
CLE0101/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/2	3/3	3/2	3/2	3/3	3/2	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
ODJ0301/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		

Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/2	3/2	3/2	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
RYE0401/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/2	3/2	3/3	3/2	3/3	3/3	3/3	3/3	3/3
KID0201/02	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
MCE0402	**GHX**	**GHY**	**GHZ**	**THX**	**THY**	**THZ**	**STX**	**STY**	**STZ**	**ELBFE**	**ELBPS**
Abduction	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
External rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
Internal Rotation	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3		
HTM	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTS	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
HTN	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3

Table 2: Obstetric brachial plexus palsy participants excluded from final data set after average traces were plotted on individual graphs and assessed based on rules of data reduction

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; ABD: Abduction; ER: External Rotation: IR: Internal Rotation; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck :Code for discarded trials: Red – Insufficient marker view; Blue –Gimbal Lock (GL) not correctable; Brown - GL Pre-movement; Green – Not true movement based on visual analysis of stick figure

	GHX	GHY	GHZ	THX	THY	THZ	TSRP	TSLM	TSAP	ELBFE	ELBPS
ABD	PAN_T1/2 MUM_T2		PAN_T1/ 2 MUM_T2	MUM-T2		MUM_T2	MUM_T2 CLE_T1	MUM_T2 CLE_T1	MUM_T2		
ER	**PAN_T1/2**		**PAN_T1/ 2**								
IR	MUM_T2		MUM_T2	MUM_T2		MUM_T1					
HTM				MUM_T2			KID_T1			PAN_T1	PAN_T1
HTS	PAN_T1/2 MUM_T2		PAN_T2 MUM_T2	MUM_T2		MUM_T2					
HTN	PAN_T1/2 MUM_T2	MUM T2	PAN_T1/ T2 MUM_T2	CLE_T1 MUM_T2	MUM_ T2	CLE_T1 MUM_T2	CLE_T1 MUM_T2	CLE_T1 MUM_T2	CLE_T1 MUM_T1	PAN_T1	PAN_T1 MUM_T2

Appendix 3.9: Trials used to calculate mean (standard deviation) waveform for typically developing children

Table 1: Number of trials used to calculate mean (standard deviation) waveform for TDC performance of task for initial data exploration

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX : Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck

	GHX	GHY	GHZ	THX	THY	THZ	STX	STY	STZ	ELBFE	ELBPS
Abduction	29	29	27	29	29	28	29	29	29	-	-
External rotation	24	25	24	24	24	25	25	23	25	-	-
Internal Rotation	24	29	22	24	29	24	29	29	27	-	-
HTM	29	30	28	25	30	25	30	29	30	30	30
HTS	24	30	24	24	30	24	27	28	28	-	-
HTN	28	28	28	27	28	28	28	28	28	28	27

Table 2: Trials excluded from data analysis following visualisation in excel graph as per rules of data reduction

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX : Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; ABD: Abduction; ER: External Rotation; IR: Internal Rotation: HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck

	GHX	GHY	GHZ	THX	THY	THZ	STX	STY	STZ	ELBFE	ELBPS
ABD	MOR0202_11	MOR0202_11	MOR0202_11/FAS0202_13/14	MOR0202_11	MOR0202_11	MOR0202_11/GEM1003_23	MOR0202_11	MOR0202_11	MOR0202_11	-	-
ER	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23:TAC0302_15	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23	MOR0202_ 20:ROJ0302_15/16:FAS0202_21/23 TAC0302_15	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23:ROB0202_15	MOR0202_20:ROJ0302_15/16:FAS0202_21/23/24	ROJ0302_15/16:MOR0202_20:FAS0202_21/23	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23:KEC1203_14:ROB0202_14	MOR0202_20:ROJ0302_15/16_:FAS0202_21/23	-	-
IR	FAS0202_25/26/27:GEM1003_27/28:MOR0202_21	FAS0202_26	FAS0202_25/26/27:GEM1003_27/28:MOR0202_21/22/23	FAS0202_25/26/27:GEM1003_27/28/29	FAS0202_26	FAS0202_25/26/27:GEM1003_27/28/29	FAS0202_26	FAS0202_26	FAS0202_26:TAF0102_20:WAE0402_17	-	-
HTM	FAS0202_18	-	FAS0202_18/19	GEM1003_18/20:	-	GEM1003_18/20:	-	ROJ0302_07	-	-	-

	GHX	GHY	GHZ	THX	THY	THZ	STX	STY	STZ	ELBFE	ELBPS
				FAS0202_18/19/20		FAS0202_18/19/2					
HTS	FAS0202_6/7/8: GEM1003_33/34/35		FAS0202_6/7/8: GEM1003_33/34/35	FAS0202_6/7/8: GEM1003_33/34/35		FAS0202_6/7/8: GEM1003_33/34/35	TAC0302_29/30	TAC0302_29/30	GEM1003_33/34/35	-	FAS0202_6/7/8: GEM1003_33/34/35
HTN	FAS0202_15/17	FAS0202_15/17:	FAS0202_15/17	FAS0202_15/17	FAS0202_15/17 GEM1003_32	FAS0202_15/17	FAS0202_15/17	FAS0202_15/17	FAS0202_15/17	FAS0202_15/17	FAS0202_15/16/17

Appendix 3.10: Normal distribution of variables

Task 1: Abduction: Shapiro Wilk Results

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX	0.122		0.129			0.041		
GHY	0.653			0.004	0.365			
GHZ	0.303		0.623			0.032		
THX		0.042	0.117		0.5			
THY		0		0.01		0.023		
THZ	0.066		0.087		0.087			
STX	0.495		0.979		0.164			
STY	0.787		0.392		0.302			
STZ	0.97		0.068		0.121			
Duration								0.036

Task 2: External Rotation: Shapiro Wilk Results

GHX:Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulorthoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX	0.526		0.513			0		
GHY		0.013		0.013	0.519			
GHZ	0.537		0.26			0.042		
THX	0.869			0.046	0.134			
THY		0.016	0.48			0.008		
THZ		0.037	0.396			0		
STX	0.211		0.935		0.6			
STY	0.114			0.026		0.022		
STZ	0.894		0.768			0.011		
Duration								0.001

Task 3: Internal Rotation: Shapiro Wilk Results

GHX:Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulorthoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX		0.019	0.817			0.056		
GHY		0.034	0.414			0.026		
GHZ	0.068		0.564		0.066			
THX	0.409		0.855		0.22			
THY		0.058	0.561		0.152			
THZ	0.46		0.298		0.665			
STX	0.229		0.952			0.019		
STY	0.29		0.471		0.278			
STZ	0.308		0.98		0.119			
Duration								0.005

Task 4: Hand to Mouth – Shapiro Wilk Results

GHX:Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX	0.29		0.262			0.048		
GHY	0.746		0.475		0.069			
GHZ	0.336		0.312		0.267			
THX	272		0.552		0.1			
THY		0.026	0.96			0.032		
THZ	0.508		0.608		0.104			
STX	0.239		0.461			0.001		
STY	0.235		0.064			0.044		
STZ	0.232		0.854			0		
ELBFE	0.575		0.304		0.347			
ELBPS	0.165			0.003	0.737			
Duration							0.178	

Task 5: Hand to Neck – Shapiro Wilk Results

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX	0.718		0.854		0.235			
GHY	0.379		0.999		0.828			
GHZ	0.231		0.572		0.606			
THX	0.087		0.82		0.33			
THY		0.034	0.86		0.691			
THZ	0.589		0.741		0.104			
STX	0.243		0.22			0.002		
STY	0.776		0.215		0.056			
STZ	0.827		0.782		0.121			
ELBFE	0.109		0.544			0.017		
ELBPS	0.796		0.129		0.592			
Duration								0.163

Task 6: Hand to Spine– Shapiro Wilk Results

GHX: Glenohumeral plane of elevation; GHY: Glenohumeral elevation; GHZ: Glenohumeral axial rotation; THX: Thoracohumeral plane of elevation; THY: Thoracohumeral elevation; THZ: Thoracohumeral axial rotation; STX: Scapulothoracic retraction/protraction; STY: Scapulothoracic lateral/medial rotation; STZ: Scapulothoracic anterior/posterior tilt; ELBFE: Elbow flexion/extension; ELBPS: Elbow pronation/supination; HTM: Hand to mouth; HTS: Hand to spine; HTN: Hand to neck; EP: End point; N: Normally Distributed; NN: Not Normally Distributed; SP: Start Point: ROM: Range of motion; D: Duration

	EP_N	EP_NN	SP_N	SP_NN	ROM_N	ROM_NN	D_N	D_NN
GHX	0.179		0.404		0.5			
GHY	0.836		0.075		0.294			
GHZ	0.219		0.921		0.501			
THX	0.6		0.911		0.18			
THY	0.394		0.404		0.394			
THZ	0.268		0.287		0.29			
STX	0.154		0.937		0.051			
STY		0.008	0.722		0.53			
STZ	0.447		0.062		0.127			
ELBFE		0.015	0.93		0.194			
ELBPS	0.154			0.011	0.075			
Duration								0.088

Appendix 4.1: Summary of methodology studies investigating reliability of three dimensional upper limb motion analysis in paediatric populations

AM: Acromial Method; TDC: Typically Developing Children; CP: Cerebral Palsy; UL: Upper Limb; HCP: Hemiplegic Cerebral Palsy; OBPP: Obstetric Brachial Plexus Palsy; M: Male; F: Female; Age: years(±Standard deviation) NC: Narakas Classification; MACS: Manual Ability Classification System; PTA: point of task achievement; ICC: Intraclass Correlation Coefficient; CMC: Coefficient of Multiple Determination; SEM: Standard Error of Measurement; RMSE-Root Mean Square Error; CMD: Coefficient of Multiple Determination.

Study	Biomechanical Model	Joint Rotation Sequence & Coordinate Systems	Participants	Tasks	Joints reported	Type of reliability, session number, interval, evaluator	Statistics
Mackey et al., 2005	21 marker model; 7 segments: pelvis, right/left side trunk/arm/forearm each a rigid segment defined by 3markers 8 camera system @ 60hz	Joint coordinate systems defined by Grood & Sunday (1983) UL joint centres defined as virtual markers from offsets of 2 external markers	10 HCP 6 M (age 9±3) 4 F (age 12±4) Affected side	Hand to mouth Hand to top of head	Trunk, Shoulder Elbow	Intra-session Inter-session 2sessions, 1 week apart 3 trials in each session	CMC of kinematic waveform
Fitoussi et al., 2006	Rigid segment model: rigid tripods and anatomical landmarks of trunk/arm/forearm/hand Vicon motion analysis 6 cameras	Static calibration at rest Not reported	15 HCP Age 12 years Affected and unaffected side	Cookie Test Displacement Task	Trunk Shoulder Elbow Wrist	Intra-session Preliminary inter-session with one TDC One session 3 trials	CMC/Mean (SD) of kinematic waveform and angle at PTA

Study	Biomechanical Model	Joint Rotation Sequence & Coordinate Systems	Participants	Tasks	Joints reported	Type of reliability, session number, interval, evaluator	Statistics
Bialocerkowski et al., 2006	V-scope (Eshed Robotec Inc. USA) Portable, relatively inexpensive movement analysis system (2D)	Own segmental models	30 OBPP 18 F 12 M Age 2year 6months (±1y2m) 13 NC 1 11 NC II 6 NC III	Active Elbow flexion/extension Active Shoulder abduction/flexion	Shoulder Elbow	Inter-session Inter-observer (generalist & paediatric physiotherapist) 2 sessions One week apart 3 trials	ICC/SEM of range of movement Paired t-test
Schneiberg et al., 2010	Optotrak 3020 (Northern Digital Inc) or Vicon both at 100hz Markers placed on specified anatomical landmarks and reference points	Positional data (x,y,z) were low pass filtered (10hz) to plot 3D trajectories Joint angles computed by vectors joining defined markers (Not ISB)	13 children with CP 10 HCP 3 quadriplegia 3 M 10 F Age 9(±1.6) MACS level II 5/ III 4/ IV 4 More affected arm	Trunk Shoulder Elbow Trajectory smoothness/ straightness	Simulated feeding from three target points	Inter-session 3 sessions over 5weeks 0wk/2.5wks/5wks 10trials Same evaluator	Mean (SD)/ICC of angle at PTA
Reid et al., 2010	University of Western Australia's upper limb model	ISB recommendation for coordinate systems Cardan angle "XYZ" sequence for all joints	7 HCP 4 M 3 F MACS Level I-III Age 11.14 (±1.82) Affected limb 10TDC 5 M 5 F Age 10.5 (±1.18) Dominant limb	Reach forward to low target Reach sideways to elevated target Pronation/ Supination Hand to mouth	Trunk Shoulder Elbow Wrist	Intra-session Inter-session 2sessions At least 1 week apart 3 trials	CMD of Kinematic waveforms
Butler et al., 2010	Nine segment model (Aguinaldo 2007) Trunk; right/left -shoulder girdle, upper arm, forearm, hand	Variation of ISB recommendations – not specified	25 TDC 11 M 14 F Age 11(±4.1) Dominant limb 2 HCP; 2 F Age 14/15 Years Affected limb	Reach to grasp cycle	Trunk Shoulder Elbow Wrist	Intra-session Inter-session (7 TDC 3 M 4 F 11.2 (±4.4) 2 sessions 1 week apart	CMC/ Measurement error as per Schwartz et al (2004) of kinematic variables at start/PTA/return. Spearman's rank coefficient (age/ kinematic variables)

Study	Biomechanical Model	Joint Rotation Sequence & Coordinate Systems	Participants	Tasks	Joints reported	Type of reliability, session number, interval, evaluator	Statistics
Jaspers et al., 2011a	AM (van Andel et al., 2008) Vicon 12 cameras	ISB Recommendations (Wu et al 2005)	10 TDC M 6 F 4 Age 10.3(±3.2) Non-dominant limb	Reach: forwards/sideways/upwards Reach to grasp: spherical/horizontal/vertical Hand to mouth Hand to top head Hand to contralateral shoulder	Trunk Scapulothoracic Shoulder Elbow Wrist	Intra-session Inter-session 2 sessions 2-10days apart 3 trials Same evaluator	ICC/SEM Joint angle at PTA and spatiotemporal parameters Kinematic waveform error (Schwartz et al 2004)/CMC
Jaspers et al., 2011b	AM (van Andel et al., 2008) Vicon 12 cameras	ISB Recommendations (Wu et al 2005)	12 HCP M 6 F 6 MACS Level I 4 II 8 Age 10.2(±3.2) Affected limb	Reach: forwards/sideways/upwards Reach to grasp: spherical/horizontal/vertical Hand to mouth Hand to top head Hand to contralateral shoulder	Trunk Scapulothoracic Shoulder Elbow Wrist	Intra-session Inter-session 2 sessions Mean interval (5(±1.7) 3 trials Same evaluator	ICC/SEM Joint angle at PTA/spatiotemporal parameters Kinematic waveform error (Schwartz et al 2004)/CMC
Lempereur et al., 2012	AM (ISB recommendations) Vicon	Glenohumeral rotation centre using functional method ISB recommendations scapula “YXZ”; “YXY for GH joint except in gimbal lock used “ZXY” (Senk and Cheze 2006) if still has gimbal lock “ZXY” used	10 HCP 5M 5 F 11.8(±3.6) MACS Level I 1 II 9 Affected limb 10 TDC 5 M 5 F 11.2(±3.1) Non-dominant	Shoulder Flexion Shoulder Abduction Hand to mouth Hans to contralateral shoulder Hand to spine pocket	Intra-session One session 3 trials Concurrent validity with scapular locator	Thoracohumeral Scapulothoracic Glenohumeral	CMC/SEM at start/PTA Wilcoxan paired t-test at start/end/range of flexion/abduction for TDC/HCP RMSE 2way ANOVA for validity of flexion/abduction (p<0.05)

Study	Biomechanical Model	Joint Rotation Sequence & Coordinate Systems	Participants	Tasks	Joints reported	Type of reliability, session number, interval, evaluator	Statistics
Vanezis et al., 2015	AM (van Andel et al., 2008) Vicon 8 cameras	ISB recommendations except Shoulder joint centre/elbow flexion/extension axis estimated from functional movements	10 TDC M 6 F 4 Age 13.6(±4.3) Non-dominant limb	Reach up/side/forwards with horizontal grip Reach forward with vertical grip Hand to contralateral shoulder Hand to spine head Hand to spine pocket Drinking task Throw to target	Head Trunk Scapulothoracic Glenohumeral Thorcohumeral Elbow Wrist	Intra-session Inter-session 2 sessions 1week apart 3 trials	SEM spatiotemporal parameters Kinematic waveform error (Schwartz et al 2004)/CMC
Current Study	AM (van Andel et al., 2008) CODA (Charnwood Dynamics Ltd)	ISB recommendations (Wu et al 2005)	10 OBPP 7 M 4 F NC I 2 NC II 7 NC III 2 Age 10(±2.5) Affected limb	Mallet Scale (Abzug et al 2010) Abduction External rotation Internal rotation Hand to Mouth Hand to Neck Hand to spine	Thoracohumeral Scapulothoracic Glenohumeral Elbow (functional tasks)	Inter-session 2 sessions 2-14days apart 3 trials Experienced Paediatric physiotherapist	ICC/SEM/Bland and Altman Plots for spatiotemporal parameters, range of motion and joint angle at PTA