QUANTITATIVE ANALYSIS OF UPPER LIMB FUNCTION AMONG CHILDREN WITH CEREBRAL PALSY DURING A REACH AND GRASP CYCLE

A DISSERTATION
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DOCTOR OF PHILOSOPHY

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Abstract

The ability to reach, grasp, transport, and release objects is central to activities of daily living, such as feeding and grooming. However, children with cerebral palsy (CP) often have difficulty with these tasks, limiting their independence. While it is challenging to characterize and quantify specific upper limb movement disorders in CP, it is essential for identifying the underlying neural correlates and etiology, assessing movement disorder subtypes, i.e. spasticity, dystonia, and ataxia, which affect treatment selection, and measuring treatment outcomes. Current methods for measuring upper limb motion deficits are based predominantly on subjective, observational assessments. Thus, we have proposed three-dimensional motion analysis of the upper limbs during a Reach & Grasp Cycle to address the need for a standardized protocol for analysis of upper limb motion. The Reach & Grasp Cycle is a sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging for individuals with CP.

Using a biomechanical model of the trunk and upper limbs, we calculated three-dimensional joint kinematics and temporal-spatial parameters for 30 typically developing (TD) children and 25 children with CP and upper limb involvement, ages 5-18 years, using an optoelectric motion analysis system. Consistent normative data and clinically significant differences in joint motions and temporal-spatial parameters between the CP and TD children suggest the Reach & Grasp Cycle is a repeatable protocol for objective and quantitative clinical evaluation of functional upper limb motor performance.

Next, we derived a single score of upper limb pathology from upper limb kinematics called the Pediatric Upper Limb Motion Index (PULMI). The root-mean-square difference was calculated between the data of each child with CP and the average from the TD population for eight kinematic variables over the Reach & Grasp Cycle. The raw value was then scaled such that a PULMI score ≥100 indicated the absence of upper limb pathology, and every 10 points below 100 corresponded to one standard deviation away from the TD PULMI mean. The PULMI was significantly different between the TD children and children with CP (Wilcoxon Z=-5.06, p<.0001),
and between children with spastic CP and dyskinetic CP ($Z=2.47$, $p<0.0135$). There was a strong negative correlation between the PULMI and the standard Manual Ability Classification System for all children with CP (Spearman’s rho $= -0.78$, $p<0.001$), indicating good validity of the PULMI. In addition, four key temporal-spatial parameters (movement time, index of curvature during reach, ratio of the peak velocity of the transport and reach phases of the Reach & Grasp Cycle, and total number of movement units) revealed differences in movement patterns between CP and TD children. Furthermore, a multi-variable logistic regression of these temporal-spatial parameters was derived which correctly predicted 19 of 22, or 86%, of movement disorder sub-types (spastic versus dyskinetic CP).

This research describes a pediatric upper limb motion index (PULMI) for children with cerebral palsy (CP) that provides information regarding the quality of upper limb motion during a functional sequence of tasks. The PULMI, calculated from upper limb kinematics, and key temporal-spatial parameters of the Reach & Grasp Cycle offer a quantitative approach to analyzing the quality of upper limb function in children with CP and identifying specific types of movement deficits. It is suggested for use in both research and clinical applications.
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I. Introduction

The ability to reach, grasp, transport, and release objects is central to activities of daily living, such as feeding and grooming. However, children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements (Steenbergen, Hulstijn et al. 1998) and the coordination of fingertip forces during grasp and release (Eliasson, Gordon et al. 1991; Eliasson and Gordon 2000). Cerebral palsy describes a heterogeneous group of disorders affecting the development of movement and posture that limits physical activity and is caused by non-progressive insult to the developing brain (Bax, Goldstein et al. 2005).

Upper limb impairment in children with hemiplegic CP varies depending on the severity and type of abnormal muscle tone or coordination, i.e. spasticity, dystonia, athetosis, or ataxia, which may occur separately or in combination. In spastic CP, upper limb involvement varies from mild clumsiness in fine motor control to fixed muscle contractures preventing active extension of the elbow, wrist or fingers, or supination of the forearm (Manske 1990). Upper limb impairment in dyskinetic CP (dystonia or athetosis) manifests as involuntary, uncontrolled, recurring, occasionally stereotyped movements (Surveillance of Cerebral Palsy in Europe 2000). Dystonia is a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both (Sanger, Chen et al. 2010), while athetosis is defined as a slow, continuous, involuntary writhing movement that prevents maintenance of a stable posture (Sanger, Chen et al. 2010). Finally, ataxia is defined as an inability to generate a normal or expected voluntary movement trajectory that cannot be attributed to weakness or involuntary muscle activity about the affected joints (Sanger, Chen et al. 2006).

While it is challenging to characterize and quantify specific upper limb movement disorders, it is essential to identifying the underlying neural correlates and etiology, as well as for assessing the quality of movement and treatment outcomes. Unfortunately, the currently practiced methods for characterizing specific upper limb motion deficits and measuring the functional outcomes of interventions are based predominantly on subjective, observational assessments.
Three-dimensional motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function during gait in individuals with CP (Gage and Novacheck 2001; Mackey, Walt et al. 2005). Motion analysis of the upper limb is more technically challenging due to the non-cyclical nature of functional use and the increased range and complexity of motion at the shoulder joint (Rau, Desselhorst-Klug et al. 2000). As a result, few researchers have used motion analysis to characterize upper limb kinematics until recently (Mackey, Walt et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007; Petuskey, Bagley et al. 2007), and there remains no generally accepted or standardized evaluation protocol (Kontaxis, Cutti et al. 2009).

**Focus of the Thesis**

We propose the Reach & Grasp Cycle and the biomechanical model described within this dissertation to address the lack of a standardized protocol for analysis of upper limb motion. The Reach & Grasp Cycle is a sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging enough to reveal key motor deficits in individuals with movement disorders. Joint kinematics are calculated according to a variation of the method proposed by the Standardization and Terminology Committee of the International Society of Biomechanics (Wu, van der Helm et al. 2005). In addition to joint kinematics, the duration, velocity, smoothness and trajectory of movement provide important information regarding the quality of upper limb motion (Chang, Wu et al. 2005), and are able to help delineate the contribution of different etiologies and associated movement deficits that impair upper limb function in CP. The Pediatric Upper Limb Motion Index (PULMI) was developed within the context of this thesis to provide a comprehensive, quantitative index of movement quality and to quantify differences in movement patterns between spastic, dyskinetic, and ataxic CP. The PULMI is suggested for use in both research and clinical applications.
Dissertation Overview

Chapters III, IV, and V were written as self-contained original journal articles. Therefore, the introduction and methods sections within these chapters may contain information redundant to the Background (Chapter II).

Chapter III was published in *Gait & Posture* 32 (2010): 72-77. The purpose of this study was to assess the utility of the Reach & Grasp Cycle using three-dimensional motion analysis. Normative kinematic patterns of reaching, grasping, transporting, and releasing an object were characterized for 30 typically developing children, and upper limb kinematics for two children with CP are reported as case studies. Chapter IV was published in *Gait & Posture* 32 (2010): 301-306. Chapter IV focuses on temporal-spatial characteristics of 30 typically developing children and differences among 25 children with spastic, dyskinetic, or ataxic CP during the Reach & Grasp Cycle.

Chapter V has been prepared for submission to a scientific journal. The focus of Chapter V is the development of a comprehensive quantitative profile of upper limb function based on three-dimensional kinematics and temporal-spatial parameters. Chapter V demonstrates that the Pediatric Upper Limb Motion Index (PULMI) index is robust, valid, and reliable. The profile outlines differences between neuromotor abnormalities in spastic, dyskinetic, and ataxic CP, and is useful for research and clinical applications.

Original authors include:

Chapter III – Erin E. Butler, Amy L. Ladd, Stephanie A. Louie, Lauren E. LaMont, Wendy Wong, Jessica Rose


Chapter IV – Erin E. Butler, Amy L. Ladd, Lauren E. LaMont, Jessica Rose


Chapter V - Erin E. Butler and Jessica Rose

*Manuscript in preparation*
II. Background

This section provides background information relevant for understanding the methods, results, and conclusions of this dissertation. This dissertation focuses on a novel quantitative measure of upper limb function in children with cerebral palsy, utilizing three-dimensional motion analysis techniques.

Cerebral Palsy

Cerebral palsy (CP) is the most common motor disorder among children born prematurely, affecting approximately 15% of very low birth weight (VLBW) preterm infants, <1500g, <32 weeks gestation (Pinto-Martin, Riolo et al. 1995), and in the overall population, 2.4 children per 1000 births in the United States (Hirtz, Thurman et al. 2007). According to the Executive Committee for the Definition of Cerebral Palsy (Bax, Goldstein et al. 2005), “Cerebral palsy (CP) describes a group of disorders of the development of movement and posture causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, cognition, communication, perception and/or behavior, and/or by a seizure disorder.”

The pattern and extent of the motor disorder in CP can be specified according to anatomic distribution. The limb distribution of CP is most commonly classified into hemiplegia, which involves primarily the upper and lower limbs on one side of the body; diplegia, which involves primarily the lower extremities; triplegia, which describes a hemiplegic pattern on one side involving the upper extremity, with a diplegic pattern in the lower extremities; and quadriplegia, which involves the trunk and all four limbs (Miller 2005). The focus of this dissertation is upper limb function; therefore, only patients with hemiplegia, triplegia, or quadriplegia were considered.

In addition to anatomic distribution, the predominant type of motor disorder can further categorize patterns of CP, e.g. spasticity, dyskinesias (dystonia or athetosis), and ataxia (Surveillance of Cerebral Palsy in Europe 2000). Spastic CP is characterized by spasticity, i.e. a velocity-dependent response to stretch, along with
loss of selective motor control and weakness. It is thought to be caused by injury to descending corticospinal and corticobulbar (pyramidal) tracts (Staudt, Pavlova et al. 2003). The well-observed effects of spasticity on skeletal muscle in patients with CP include decreased longitudinal growth of the muscle fiber length, decreased muscle volume, change in motor unit size, and altered fiber type distribution and neuromotor junction type (Tardieu, Huet de la Tour et al. 1982; Rose, Haskell et al. 1994; Lieber and Friden 2002; Rose and McGill 2005; Malaiya, McNee et al. 2007). In the mouse model, spasticity causes loss of 45% of the longitudinal growth of the muscle fiber, resulting in contractures (Ziv, Blackburn et al. 1984). Muscle contractures are common in children with spastic CP and a primary focus of therapeutic and surgical interventions.

Dyskinesias, specifically dystonias, are thought to result from damage to the subcortical nuclei, which constitute the basal ganglia and thalamus (Bax, Tydeman et al. 2006). Damage to the basal ganglia may result in involuntary movements, e.g. tremors, chorea, athetosis, and dystonia. Dystonia is a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both (Sanger, Chen et al. 2010). Athetosis is characterized by an inability to maintain the fingers, toes, tongue, or other body parts in a stable position. Athetosis is defined as a slow, continuous, involuntary writhing movement that prevents maintenance of a stable posture (Sanger, Chen et al. 2010).

Ataxia is defined as an inability to generate a normal or expected voluntary movement trajectory that cannot be attributed to weakness or involuntary muscle activity about the affected joints (Sanger, Chen et al. 2006). The cerebellum participates in the planning and coordination of movement; thus, cerebellar damage may result in an inability to judge distances accurately and cause intention tremor during voluntary movement (Kandel, Schwartz et al. 2000), as seen in patients with ataxic CP.

Hypoxic-ischemia or inflammatory insult to the developing brain during the early third trimester of gestation is the major etiological factor in CP (Johnston, Trescher et al. 2001; Volpe 2001; Payam and Andrew 2002) and most often results in
damage to the periventricular white matter. Periventricular leukomalacia (PVL) is the most common form of periventricular white matter injury found in the VLBW preterm child (de Vries, Groenendaal et al. 1999; Inder, Huppi et al. 1999; Kuban, Sanocka et al. 1999; Huppi, Murphy et al. 2001). Selective vulnerability of this region to hypoxic-ischemia brain injury is thought to be due to insufficient vascularization of the developing blood supply in the periventricular region of the lateral, third, and fourth ventricles of the brain in infants born before 32 weeks gestational age (Hoon and Melhem 2000). Another form of periventricular white matter injury commonly found in preterm and full-term children with hemiplegia consists of unilateral periventricular venous infarction, as a result of hemodynamic changes secondary to intraventricular hemorrhage (de Vries, Roelands-van Rign et al. 2001; Takanashi, Barkovich et al. 2003). Immature oligodendroglia are particularly susceptible to white matter injury, leading to reduced myelination in white matter tracts.

In summary, loss of selective motor control, weakness, and spasticity in CP are thought to result from injury to descending corticospinal tracts, whereas deficits in motor planning, balance, and coordination in CP are attributed to abnormalities in the basal ganglia, thalamus, and cerebellum, resulting in dyskinetic or ataxic CP. Spasticity, dyskinesia, and ataxia may occur in combination in individuals with CP.

**Upper Limb Deficits and Treatment in Cerebral Palsy**

The range of upper extremity involvement in children with hemiplegic CP varies from mild clumsiness in fine motor control to fixed muscle contractures with an inability to actively extend the elbow, wrist or fingers, or supinate the forearm (Manske 1990). Spastic muscles and weakness of antagonistic muscles contribute to fixed muscle contractures. The typical pattern of spastic joint deformities of the upper extremity include shoulder internal rotation, elbow flexion, forearm pronation, wrist flexion and ulnar deviation, thumb-in-palm (adduction of the thumb against the palm of the hand), and finger swan neck (hyperextension of the proximal interphalanageal (PIP) joint, flexion of the distal interphalanageal (DIP) joint, and sometimes flexion of the metacarpophalanageal (MCP) joint) or clenched fist deformity (Van Heest 1996). Children with hemiplegic CP often have difficulty with the timing of reaching
movements, difficulty with grasping and with the coordination of fingertip forces during precision grasp (Eliasson, Gordon et al. 1991).

Most patients with spastic CP are treated non-surgically with therapy for passive range of motion, static nighttime splinting, orthoses, or botulinum toxin injections for fixed deformities, or with coaching in functional adaptation for dynamic deformities. Constraint-induced movement therapy is a form of therapy in which the unimpaired arm is constrained and the child is encouraged to use the impaired arm for everyday activities. Movement is reinforced through shaping techniques, e.g. practicing a target movement in isolation of other movements under a time constraint.

Surgical treatment for upper extremity dysfunction due to joint deformity may include soft tissue release of deforming spastic muscles, tendon transfers to augment antagonistic muscle activity, and joint stabilization procedures (Van Heest, House et al. 1999). Soft tissue releases are most commonly indicated for spastic contracture, with tendon transfers added when the spastic deformity is more severe and voluntary motor control is adequate. Joint stabilization procedures are indicated for severe joint contractures or joint instability.

Dyskinesias and ataxia are typically treated with therapeutic interventions or oral medications. Dystonia is a contraindication to muscle lengthenings or transfers (Miller 2005).

**Upper Limb Motor Evaluation Tools**

There currently exist several evaluation tools to assess upper limb function. These include the Bayley Motor Scales (1969), the Jebsen-Taylor Test of Hand Function (Taylor et al., 1973), and the Peabody Fine Motor Scale (Folio and Fewell 1983). However, these assessment tools do not provide information regarding the quality of movement and are not standardized for the cerebral palsy population. The Erhardt Developmental Prehension Assessment (1982) meets the above two criteria but it is not quantifiable.

The Quality of Upper Extremity Skills Test (QUEST, DeMatteo et al., 1992), Melbourne Assessment of Unilateral Upper Limb Function (‘Melbourne Assessment’, Johnson et al., 1994), and the Shriners Hospital for Children Upper Extremity
Evaluation (SHUEE, Davids et al., 2006) provide information concerning the quality of movement based on observational assessments, are standardized for the cerebral palsy population, and provide quantifiable scores. The QUEST, Melbourne Assessment, and SHUEE measurement tools have been validated through concurrent assessment of a previously validated measurement tool. However, they are lengthy and require subjective observational assessment by a trained clinician.

The QUEST was developed to assess change in the quality of upper extremity activities. There are a total of 174 sub-tasks within the four domains of dissociated movements, grasp, weight bearing, and protective extension. Each sub-item is scored on a dichotomous scale: ‘able to complete’ or ‘not able to complete’. The QUEST has been validated for children with neuromotor dysfunction and spasticity.

The Melbourne Assessment is a clinical test battery that quantifies the quality of upper limb motor function for children with neurological impairment. It consists of twelve test items: hand to mouth, pronation/supination, grasp of crayon, drawing, grasp of pellet, manipulation of cube, release of crayon, release of pellet, hand to buttock, reach in sideways direction to elevated position, reach forwards, reach in forwards direction to elevated position. These test items are similar to sub-tasks in the dissociated movements and grasp domains of the QUEST. The Melbourne Assessment is recorded on videotape and the quality of movement, i.e. range of movement, target accuracy, and fluency, is scored by a clinician.

The SHUEE is a video-based tool for the assessment of upper extremity function in children with hemiplegic CP. A clinician evaluates active and passive range of motion from the shoulder to the fingers, spontaneous use of the involved extremity during nine functional tasks, segmental alignment of the affected extremity during 16 selected tasks, and grasp and release performance.

The Manual Ability Classification Score (MACS) is a functional classification system that characterizes the extent to which an individual with CP, ages 4-18 years, has limited hand and arm motor function and describe the individual uses their hands to handle objects in daily activities. (Eliasson, Krumlinde-Sundholm et al. 2006). The five levels of the MACS are based on the children's self-initiated ability to handle
objects and their need for assistance or adaptation to perform manual activities in everyday life. The MACS differs from the tests described above in that it is a functional classification system rather than an upper limb performance evaluation tool. Reliability of the MACS has been tested on children with hemiplegia (n=52), diplegia (n=70), tetraplegia (n=19), ataxia (n=6), dyskinesia (n=19), and unspecified CP (n=2).

**Three-dimensional Motion Analysis of the Upper Limb**

Motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function during gait in individuals with CP (Gage and Novacheck 2001; Mackey, Walt et al. 2005). Motion analysis of the upper limb is more technically challenging due to the non-cyclical nature of functional use and the increased range and complexity of motion at the shoulder joint (Rau, Disselhorst-Klug et al. 2000). As a result, few researchers have used motion analysis to characterize upper limb kinematics until recently (Mackey, Walt et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007; Petuskey, Bagley et al. 2007). In addition to joint kinematics, the duration, velocity, smoothness and trajectory of movement can provide important information regarding the quality of upper limb motion (Chang, Wu et al. 2005), and may help delineate the contribution of different etiologies and associated movement deficits that impair upper limb function in CP. Other studies have reported temporal-spatial parameters of reaching and/or grasping (Kuhtz-Buschbeck, Stolze et al. 1998; Chang, Wu et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Gordon, Keller et al. 2006; Coluccini, Maini et al. 2007; Rönnqvist and Rösblad 2007). However, there remains no standardized protocol for 3-D upper limb motion to report joint kinematics or temporal-spatial parameters (Jaspers, Desloovere et al. 2009; Kontaxis, Cutti et al. 2009), making it difficult to assess repeatability, compare results across studies, and facilitate the selection and planning of treatment interventions for children with CP and upper limb involvement.
III. Three-dimensional kinematics of the upper limb during a Reach & Grasp Cycle for children

The ability to reach, grasp, transport, and release objects is essential for activities of daily living. The objective of this study was to develop a quantitative method to assess upper limb motor deficits in children with cerebral palsy (CP) using three-dimensional motion analysis. We report kinematic data from 30 typically developing (TD) children (14 males, 16 females; ages 5-18 years) and 2 children with spastic hemiplegic CP (2 females, ages 14 and 15 years) during the Reach & Grasp Cycle. The Cycle includes six sequential tasks: reach, grasp cylinder, transport to mouth (T1), transport back to table (T2), release cylinder, and return to initial position. It was designed to represent a functional activity that was challenging yet feasible for children with CP. For example, maximum elbow extension was 45±11 degrees flexion in the TD group. Consistent kinematic patterns emerged for the trunk and upper limb: coefficients of variation at point of task achievement for reach, T1, and T2 for trunk flexion-extension were (.10,.10,.10), trunk axial rotation (.05,.05,.05), shoulder elevation (.13,.14,.13), elbow flexion-extension (.25,.05,.23), forearm pronation-supination (.08,.11,.11), and wrist flexion-extension (.24,.20,.22). The children with CP demonstrated reduced elbow extension, increased wrist flexion and trunk motion, with an increased tendency to actively externally rotate the shoulder and supinate the forearm during T1 compared to the TD children. The consistent normative data and clinically significant differences in joint motion between the CP and TD children suggest the Reach & Grasp Cycle is a repeatable protocol for objective clinical evaluation of functional upper limb motor performance.
Introduction

The ability to reach, grasp, transport, and release objects is central to activities of daily living, such as feeding and grooming. Children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements (Steenbergen, Hulstijn et al. 1998) and the coordination of fingertip forces during grasp and release (Eliasson, Gordon et al. 1991; Eliasson and Gordon 2000). The severity of upper limb involvement in children with hemiplegic CP varies from mild clumsiness in fine motor control to fixed muscle contractures that limit active extension of the elbow, wrist or fingers, and supination of the forearm (Manske 1990). Therapeutic and surgical interventions primarily focus on improving muscle balance and wrist position to maximize hand function (Van Heest, House et al. 1999); however, the methods for characterizing specific upper limb motion deficits and measuring the functional outcomes of these interventions are varied and mostly subjective.

Upper limb function has traditionally been evaluated by the Bayley Motor Scale (Bayley 1969), Jebsen-Taylor Test of Hand Function (Taylor, Sand et al. 1973), and Peabody Fine Motor Scale (Folio and Fewell 1983). However, such tests only assess the quality of upper limb movement based on observational analysis and are not standardized for the CP population. The Erhardt Developmental Prehension Assessment (Erhardt 1982) is standardized for children with CP, but it assesses the quality of upper limb movement based on observational analysis only and its scoring system is non-quantifiable. Recently, additional evaluative tools have emerged, including the Quality of Upper Extremity Skills Test (QUEST) (DeMatteo, Law et al. 1992), the Melbourne Assessment of Unilateral Upper Limb Function (Johnson, Randall et al. 1994), and the Shriners Hospital for Children Upper Extremity Evaluation (SHUEE) (Davids, Peace et al. 2006). These tools provide information concerning the quality of movement, are standardized for the CP population, and provide a quantifiable score of performance, yet they are lengthy, require the child to perform numerous tasks, and are based on subjective, observational analysis.

Motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function during gait in
individuals with CP (Gage and Novacheck 2001; Mackey, Walt et al. 2005). Motion analysis of the upper limb is more technically challenging due to the non-cyclical nature of functional use and the increased range and complexity of motion at the shoulder joint (Rau, Disselhorst-Klug et al. 2000). As a result, few researchers have used motion analysis to characterize upper limb kinematics until recently (Mackey, Walt et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007; Petuskey, Bagley et al. 2007), and there remains no generally accepted or standardized evaluation protocol (Kontaxis, Cutti et al. 2009). We propose the Reach & Grasp Cycle and the model described below to address these issues. The Reach & Grasp Cycle is a sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging enough to reveal key motor deficits in individuals with movement disorders. Joint kinematics were calculated according to a variation of the method proposed by the Standardization and Terminology Committee of the International Society of Biomechanics (Wu, van der Helm et al. 2005).

The purpose of this study was to assess the utility of the Reach & Grasp Cycle using three-dimensional motion analysis. Normative kinematic patterns of reaching, grasping, transporting, and releasing an object were characterized for 30 typically developing children, and upper limb kinematics are reported for two children with CP.

**Methods**

**Participants**

Thirty typically developing (TD) children and adolescents (14 males and 16 females, ages 5-18 years, mean age 10.9±4.1 years) participated in this study. Participants had no history of orthopedic or neurological abnormalities. Two children with moderate, left-sided spastic hemiplegic CP (2 females, ages 14 and 15 years) were evaluated for comparison purposes. The protocol was approved by the Stanford University Institutional Review Board. Informed consent was obtained from the
children’s parent or guardian; written assent was acquired from children 7 years and older.

**Table 3-1:** Placement of the retro-reflective markers for motion capture.

<table>
<thead>
<tr>
<th>Anatomic Position</th>
<th>Right or Left Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acromion process</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Clavicle</td>
<td>Right (for asymmetry)</td>
</tr>
<tr>
<td>Sternal notch</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Seventh cervical spine (C7)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Superior angle of the scapula</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Inferior angle of the scapula</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Sacrum</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Lateral humeral epicondyle</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Ulnar styloid process</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Radial styloid process</td>
<td>Right and Left</td>
</tr>
<tr>
<td>Third metacarpal-phalangeal (MCP) joint</td>
<td>Right and Left</td>
</tr>
</tbody>
</table>

**Experimental set-up**

Light-reflective markers were placed on the child’s torso and upper limbs at specific bony landmarks (Table 3-1). Participants were seated comfortably at a height-adjustable table with the hips and knees flexed 90° and both feet flat on the ground. Both arms rested on the table so that the shoulder was in a neutral position, the elbows were flexed approximately 90°, the forearms were pronated, and the wrists were held in neutral with the palms flat on the table. A cylindrical cup (height: 12.5cm, diameter: 5.5cm) was placed at 75% of the participant’s maximum reach. From the initial *start* position, each participant was instructed to *reach* forward and *grasp* the cup (Figure 3-1A), *transport* the cup to his/her mouth to simulate drinking (*T₁*) (Figure 3-1B), *transport* the cup back to its original location (*T₂*), *release* the cup, and *return* his/her arm to the initial position.
The phases and tasks of the Reach & Grasp Cycle are displayed in Figure 3-2. The TD participants were instructed to perform the task with the dominant hand; the patients with CP performed the task with the more impaired hand to assess the extent to which they deviated from the normal level of function. Three-dimensional marker position data were recorded from participants during a single Reach & Grasp Cycle after 1-2 practice trials using an eight-camera optoelectric motion analysis system recording at 100 Hz (Motion Analysis Corporation, Santa Rosa, CA), and filtered using a Butterworth filter with a cutoff frequency of 12 Hz.

Figure 3-1: Typically developing participant demonstrating the testing set-up: point of task achievement for (A) Reach, and (B) Transport to self (T).

Figure 3-2: Phases and tasks of the Reach & Grasp Cycle.
Upper limb model

Joint kinematics for the Reach & Grasp Cycle were calculated according to a variation of the method proposed by the Standardization and Terminology Committee of the International Society of Biomechanics, which defined a set of coordinate systems for various joints of the upper body based on the joint coordinate system (Wu, van der Helm et al. 2005). The upper limb model (Figure 3-3) consists of nine segments, including the trunk, right and left shoulder girdle, right and left upper arm, right and left forearm, and right and left hand. This model has been previously described by Aguinaldo et al. (Aguinaldo, Buttermore et al. 2007).

Upper limb joint centers of the shoulder, elbow, and wrist were calculated from anthropometric offsets of external markers, provided by the regression analyses of Veeger et al. (Veeger, Yu et al. 1997). The glenohumeral (shoulder) joint center was estimated relative to the three markers on the shoulder girdle: the inferior angle, spine, and acromion process of the scapula. Although scapular motion is known to be compromised by skin motion, regression errors have been found to be no more than those where the glenohumeral center is estimated from trunk based markers, particularly when shoulder elevation is less than 120 degrees (Karduna, McClure et al. 2001). The elbow joint was referenced to the plane defined by the glenohumeral joint,
the lateral epicondyle, and the wrist joint center. The wrist joint center was located midway between the radial and ulnar styloid markers.

Assumptions were made about the shoulder joint such that only glenohumeral motion was considered. Scapulothoracic and acromioclavicular motions were disregarded. Glenohumeral rotations were calculated with respect to the torso, i.e. humeral motion relative to the ipsilateral part of the torso, or shoulder girdle. Shoulder “abduction” and “flexion” were described as elevation to minimize any ambiguity associated with clinical abduction and flexion measurements. This is based directly on the ISB recommendations. The term “elevation” is used to minimize ambiguity in this rotation when the movement does not occur purely in the sagittal or frontal plane.

A joint coordinate system (JCS) was established at each upper body joint and was used to calculate the movements of segments, either with respect to the proximal segment or the global coordinate system (Figure 3-3). A JCS was defined using the hinge or medial-lateral axis (e1) of the proximal segmental coordinate system and the long axis (e3) of the distal segment. The floating axis (e2) was defined as the cross-product of the two segmental fixed axes. Sagittal movements were defined as rotations of the long axis of the segment as observed along its medial-lateral axis; frontal plane movements were rotations of the long axis of the segment as observed down its anterior-posterior axis; and transverse plane motion was defined as rotation about the long axis of the segment. It was assumed that elbow motion was primarily uniplanar (flexion-extension) and forearm pronation-supination occurred about the long axis of the forearm, i.e. the rotation of the flexion-extension axis of the wrist with respect to the flexion-extension axis of the elbow.

Data analysis

Based on the model described above, UETrak software, version 1.5.8 (Motion Analysis Corporation, Santa Rosa, CA) was used to calculate joint kinematics for eight primary motions of the trunk and dominant arm: trunk flexion-extension, trunk axial rotation, shoulder elevation, shoulder internal-external rotation, elbow flexion-extension, forearm pronation-supination, wrist flexion-extension, and wrist ulnar-radial deviation.
The velocity of the wrist marker defined the beginning and end of the Reach & Grasp Cycle. The onset of movement from the start position was identified as the first instant when the velocity of the wrist marker exceeded 5% of peak reaching velocity (van der Heide, Fock et al. 2005; Coluccini, Maini et al. 2007); the end of the Cycle was signified by a decrease in wrist marker velocity to less than 5% of the maximum velocity upon returning the arm to the initial position. Each joint motion curve was normalized to 100% of the Reach & Grasp Cycle. There was a symmetric distribution for the normalized joint angle data, as evidenced by coincidence of the mean and median values. Therefore, the mean and standard deviation were plotted for every 1% of the Cycle using an in-house custom program written in Matlab (MathWorks, Natick, MA) to create a normative database of upper limb kinematics during the Reach & Grasp Cycle.

Statistical analysis

The coefficient of variation (CV) was calculated for all eight kinematic parameters to determine the relative variability of the Reach & Grasp Cycle among TD children. Kinematic angles spanning -90 to 90° were corrected to 0 to 180° to eliminate negative numbers before calculating CV. To determine the influence of age on upper limb kinematics, Spearman’s rank correlation coefficients were computed between participant age and the eight joint motions. Kinematic values were compared at start (0% of Cycle), the points of task achievement at the end of reach, $T_1$, and $T_2$, and the end of return (100% of Cycle). The Holm-Šidák procedure was used to correct for multiple correlations. To assess repeatability of the Reach & Grasp Cycle, three trials were recorded during two testing sessions one week apart for a representative subset of 12 TD children (5 males and 7 females, mean age: 10.7±4.1 years). Intra-session and inter-session errors were calculated; the reliability of a given joint angle was measured by its standard error (Schwartz, Trost et al. 2004).
Results

Consistent kinematic patterns emerged for each of the trunk and upper limb motions during the Reach & Grasp Cycle. Joint motions during the Reach & Grasp Cycle demonstrated low variability among typically developing (TD) participants (Table 3-2). The mean CV for all phases was .12.

Table 3-2: Coefficients of variation (CV) of trunk and upper limb kinematics for each phase of the Reach & Grasp Cycle in all typically developing children (n=30).

<table>
<thead>
<tr>
<th>Joint Motion</th>
<th>Start</th>
<th>Reach</th>
<th>Transport 1</th>
<th>Transport 2</th>
<th>Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk flexion-extension</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Trunk rotation</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Shoulder elevation</td>
<td>0.36</td>
<td>0.13</td>
<td>0.14</td>
<td>0.13</td>
<td>0.39</td>
</tr>
<tr>
<td>Shoulder rotation</td>
<td>0.08</td>
<td>0.06</td>
<td>0.10</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Elbow flexion-extension</td>
<td>0.17</td>
<td>0.25</td>
<td>0.05</td>
<td>0.23</td>
<td>0.18</td>
</tr>
<tr>
<td>Pronation-supination</td>
<td>0.06</td>
<td>0.08</td>
<td>0.11</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Wrist flexion-extension</td>
<td>0.17</td>
<td>0.24</td>
<td>0.20</td>
<td>0.22</td>
<td>0.17</td>
</tr>
<tr>
<td>Wrist deviation</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Total joint excursion during the Reach & Grasp Cycle in the TD population was greatest for elbow flexion-extension (81±11°), followed by pronation-supination (49±12°), shoulder elevation (40±10°), wrist flexion-extension (35±11°), shoulder rotation (19±6°), wrist deviation (12±3°), trunk rotation (7±3°), and trunk flexion-extension (3±2°). Both children with cerebral palsy (CP) demonstrated increased trunk flexion-extension and trunk rotation, as well as reduced elbow flexion-extension excursion compared to the TD population.

There was a significant correlation between age and joint position at the point of task achievement for 2 of the 40 measures, after Holm-Šidák correction for multiple correlations: wrist deviation at the end of $T_1$ ($\rho=-.564, p=.010$) and pronation at the end of $T_2$ ($\rho=.511, p=.031$). The kinematic data were grouped together to form mean trunk and upper limb motion curves as shown in Figures 3-4 A-H. The mean±1 SD is plotted for the 30 TD children and the two children with hemiplegic CP.
Intra-session and inter-session errors in upper limb kinematics were calculated at the point of task achievement for 12 TD children, as shown in Table 3-3. Mean intra-session errors ranged from 0.8-3.7°, and mean inter-session errors ranged from 1.7-6.2°.

Figure 3-4: Upper limb kinematics during the Reach & Grasp Cycle.
Table 3-3: Intra-session and inter-session variability for a representative subset of 12 children (5 males and 7 females, ages 5-17 years, mean age: 10.7 ± 4.1 years). Values are reported in degrees for the joint motions listed at point of task achievement for each phase of the Reach & Grasp Cycle. The mean intra- and inter-session errors are reported in the last column.

<table>
<thead>
<tr>
<th>Joint Motion</th>
<th>Start</th>
<th>Reach</th>
<th>Transport 1</th>
<th>Transport 2</th>
<th>Return</th>
<th>Mean Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk flexion-extension</td>
<td>0.8</td>
<td>1.7</td>
<td>0.6</td>
<td>1.6</td>
<td>0.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Trunk rotation</td>
<td>0.8</td>
<td>1.6</td>
<td>1.2</td>
<td>1.7</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Shoulder elevation</td>
<td>1.1</td>
<td>3.4</td>
<td>1.0</td>
<td>3.1</td>
<td>3.6</td>
<td>3.9</td>
</tr>
<tr>
<td>Shoulder rotation</td>
<td>2.6</td>
<td>3.4</td>
<td>1.7</td>
<td>3.1</td>
<td>2.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Elbow flexion-extension</td>
<td>2.3</td>
<td>4.0</td>
<td>2.1</td>
<td>4.5</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Pronation-supination</td>
<td>2.2</td>
<td>4.7</td>
<td>3.0</td>
<td>4.9</td>
<td>5.6</td>
<td>8.7</td>
</tr>
<tr>
<td>Wrist flexion-extension</td>
<td>3.5</td>
<td>6.3</td>
<td>3.0</td>
<td>5.3</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Wrist deviation</td>
<td>0.9</td>
<td>2.5</td>
<td>0.6</td>
<td>2.3</td>
<td>1.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Mean ± Standard Deviation
Upper limb kinematics of the two children with moderate, left-sided spastic hemiplegic CP demonstrated substantial differences during the Reach & Grasp Cycle, i.e. greater than one standard deviation from the TD mean (Figures 3-4 A-H). Both children demonstrated increased shoulder internal rotation during reach and reduced elbow extension at the end of reach and $T_2$. Throughout the Reach & Grasp Cycle, the wrist was held in a posture of increased flexion with a reduced arc of ulnar-radial wrist deviation. In addition, both participants demonstrated an increased tendency to actively externally rotate the shoulder and supinate the forearm when bringing the cylinder to the mouth ($T_1$) and to internally rotate the shoulder and pronate the forearm when transporting the cylinder back to the table ($T_2$). In contrast, the TD children maintained approximately 10° of shoulder internal rotation and 30° of forearm pronation during $T_1$ and $T_2$.

Differences also emerged between the two participants with CP. Participant 1 sat with more trunk flexion and forward trunk rotation, and demonstrated increased shoulder elevation, wrist flexion, and ulnar deviation compared to Participant 2. Participant 1 used more forearm supination to bring the cylinder to her mouth during $T_1$ compared to Participant 2, likely due to her increased wrist flexion posture. Participant 2 sat in a more upright posture, had an increased arc of shoulder internal-external rotation, and held her wrist in increased radial deviation compared to Participant 1. Participant 2 also demonstrated increased forearm pronation during reach compared to Participant 1.

On physical examination, Participant 1 had reduced active range of elbow extension, wrist extension, and radial deviation, but she was able to actively supinate to neutral with strong effort, consistent with the kinematics. Participant 2 demonstrated a reduced active range of elbow extension, forearm supination, and wrist extension, which was also consistent with the kinematics.
Discussion

The Reach & Grasp Cycle was designed for objective quantification of upper limb motion in children. The utility of the Reach & Grasp Cycle was demonstrated by the consistent kinematic patterns among the typically developing (TD) children, and the clinically significant differences in joint motion between the children with cerebral palsy (CP) and the TD participants. The Reach & Grasp Cycle provides a quantitative analysis of motor deficits during a functional task.

Several studies have used three-dimensional motion analysis to examine upper limb motion in children with CP; although these studies have varied in the tasks performed, they have all incorporated some aspect of reaching or grasping (Mackey, Walt et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007). The Reach & Grasp Cycle represents a natural and functional behavior, such as reaching for a cup and bringing it to the mouth. Providing a functional context to a task has been shown to improve the quality of reaching movements in children with spastic hemiparesis (Volman, Wijnroks et al. 2002). In addition, the Reach & Grasp Cycle was meant to be feasible for children with motor deficits and was not intended to assess the extreme ranges of motion. Thus, the cylinder was placed at 75% of each child’s maximum reach so that the total joint excursion for each motion was less than the normal maximum range of motion.

Kinematic patterns were highly consistent among TD children during the Reach & Grasp Cycle, demonstrating a low mean coefficient of variation (CV= .11) for the functional phases of reach, T1, and T2. Despite the increased range and complexity of motion possible during unrestrained reaching movements, certain characteristic features exist, such as approximately straight hand trajectories with bell-shaped velocity profiles, tight phase-couplings of the shoulder and elbow joints, and consistent patterns of muscle activity (Morasso 1981; Soechting and Lacquaniti 1981; Jeannerod 1984; Flanders 1991). All CV values at point of task achievement for the functional phases of the Reach & Grasp Cycle were less than .25. The CV for elbow flexion-extension was lowest at the end of T1 (CV= .05) with an average elbow flexion angle of \(124\pm7^\circ\), suggesting that elbow flexion when drinking or bringing other items to the mouth is highly consistent among individuals. This consistency is also likely related to limb-size effects, i.e. the final \(T_1\) position is anatomic (hand to mouth), rather than being dependent on external
parameters, such as cup position.

For the non-functional phases of *start* and *return*, the variation in kinematic patterns among TD children was slightly greater than the functional phases (mean CV=0.13). While an effort was made to standardize the set-up, the larger CV’s for shoulder elevation between TD participants at the start and end of the Reach & Grasp Cycle (.36 and .39, respectively) suggest the initial and final positions of the participants could have been monitored more closely.

There was a significant correlation between age and joint position at the point of task achievement for 2 of the 40 kinematic measures during the Reach & Grasp Cycle: wrist deviation at the end of $T_1$, and pronation at the end of $T_2$. Younger children had less wrist radial deviation at the end of $T_1$ and less forearm pronation at the end of $T_2$ than older children. Based on a linear fit of the data, the change in wrist radial deviation at the end of $T_1$ and the change in forearm pronation at the end of $T_2$ over a period of five years would be 2.5° and 7.7°, respectively, comparable to inter-session error (Table 3-3). In a similar study, Petuskey et al. (2007) analyzed three-dimensional upper limb motion of 51 TD children during five simulated activities of daily living and found statistically significant age group-related differences in trunk flexion-extension, elbow flexion-extension, and forearm pronation-supination. However, none of these kinematic differences were greater than 10°; the authors deemed a difference of less than 10° as clinically irrelevant. Furthermore, children older than four years of age have been shown to use the same proportion of elbow extension and trunk excursion as adults during reaching (Schneiberg, Sveistrup et al. 2002). For these reasons, the kinematic data were grouped to form the mean curves shown in Figures 3-4 A-H.

The two children with CP demonstrated an increased range of trunk motion and increased wrist flexion throughout the Reach & Grasp Cycle, with increased shoulder internal rotation during *reach*, and decreased elbow extension during the *reach* and $T_2$ phases. Participant 2 also demonstrated reduced forearm supination during *reach* and $T_2$ compared to the TD children. These findings are consistent with similar studies of upper limb kinematics (Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007), either compared to TD children (Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007) or with respect to the less-impaired arm of the children with hemiplegic CP (Fitoussi, Diop et al. 2006). The upper limb motion of the children with CP reported here is also consistent with typical patterns of spastic joint deformities, including shoulder internal rotation, elbow flexion, forearm pronation, wrist flexion and ulnar
deviation (Van Heest, House et al. 1999). Moreover, the kinematic data reported also provide information regarding dynamic motion disorders present in CP. For example, both participants demonstrated an increased tendency to actively externally rotate the shoulder and supinate the forearm when bringing the cylinder to the mouth ($T_1$) and to internally rotate the shoulder and pronate the forearm when transporting the cylinder back to the table ($T_2$). For Participant 1, the increased active forearm supination while bringing the cylinder to the mouth was compensatory for her increased wrist flexion posture. For Participant 2, with decreased supination during reach, the active forearm supination while bringing the cylinder to the mouth served to posture the forearm within normal limits.

Recent studies of upper limb treatment, e.g. botulinum toxin A injections (Mackey, Miller et al. 2008), constraint-induced movement therapy (Charles, Wolf et al. 2006), and corrective surgery (Van Heest, Ramachandran et al. 2008), have used a variety of quantitative measures to assess outcome. The upper limb Reach & Grasp Cycle has the potential to offer effective and standardized quantitative evaluation of pre- and post-intervention. In addition, these quantitative measures of upper limb function may help delineate diagnoses of different movement disorders, and thus, may be important in determining structure-function relationships between brain and motor abnormalities. In a group of 51 preterm children with CP, van der Heide et al. (2005) found that an impaired quality of reaching was related to severity of brain lesions on neonatal ultrasound.

There are certain limitations that warrant consideration when interpreting the results of this study. Due to the complexity of the shoulder joint, only motion of the upper arm with respect to the ipsilateral side of the trunk was considered, i.e. glenohumeral motion. Acromioclavicular and scapulothoracic motions were not considered. Thus, the upper limb model presented here does not represent fully anatomically correct shoulder motion. In addition, the upper limb joint centers were estimated from external marker offsets. Although this is standard procedure for three-dimensional kinematic studies, soft tissue artifact and a lack of precise joint center offsets for the pediatric population contribute to systematic error. Future work will expand on the construct-validity of the Reach & Grasp Cycle for use in children with CP through correlation with the QUEST (DeMatteo, Law et al. 1992). Standardization of the start and end positions requires further refinement, given the higher CVs. Although intra- and inter-session errors were low in the TD population, we recommend collecting at least three trials. A previous three-
dimensional study of upper limb kinematics during reaching, grasping, and manipulating objects has shown moderate to good repeatability in children with CP (Mackey, Walt et al. 2005; Mackey, Walt et al. 2006).

In summary, the utility of the Reach & Grasp Cycle was demonstrated by the consistent kinematic patterns that emerged among the TD children, as well as the clinically significant differences in joint motion that arose between the children with CP and the TD children. The Reach & Grasp Cycle allows for objective quantification of upper limb motion in children.
IV. Temporal–spatial parameters of the upper limb during a Reach & Grasp Cycle for children

The objective of this study was to characterize normal temporal-spatial patterns during the Reach & Grasp Cycle and to identify upper limb motor deficits in children with cerebral palsy (CP). The Reach & Grasp Cycle encompasses six sequential tasks: reach, grasp cylinder, transport to self ($T_1$), transport back to table ($T_2$), release cylinder, and return to initial position. Three-dimensional motion data were recorded from 30 typically-developing children (14 males, 16 females; ages 5-18 years) and 25 children with CP and upper limb involvement (9 males, 16 females, age=12.3±3.7 years). Within-day and between-day coefficients of variation for the control group ranged from 0-0.32, indicating good repeatability of all parameters. The mean duration of the Cycle for children with CP was nearly twice as long as controls, 8.5±4.3sec versus 5.0±1.1sec (Wilcoxon $Z=4.07$, $P<.0001$), partly due to prolonged grasp and release durations ($P<.0001$). Peak hand velocity occurred at approximately 40% of each phase and was greater during the transport ($T_1$, $T_2$) than non-transport phases (reach, return) in controls ($P<.001$). Index of curvature was lower during transport versus non-transport phases for nearly all children. Children with CP demonstrated an increased index of curvature during reach ($Z=3.83$, $P=.0001$) and an increased total number of movement units ($Z=3.84$, $P=.0001$) compared to controls, indicating less efficient and less smooth movements. Total duration of the Reach & Grasp Cycle (Spearman’s $\rho=.665$, $P<.0001$), index of curvature during reach ($\rho=.656$, $P<.0001$), and total number of movement units ($\rho=.648$, $P<.0001$) correlated strongly with MACS score. The consistent normative data and the substantial differences between children with CP and controls reflect utility of the Reach & Grasp Cycle for quantitative evaluation of upper limb motor deficits.
Introduction

Cerebral palsy describes a heterogeneous group of disorders affecting the development of movement and posture that limits physical activity and is caused by non-progressive insult to the developing brain (Bax, Goldstein et al. 2005). Upper limb impairment in children with hemiplegic CP varies depending on the severity and type of abnormal muscle tone or coordination, i.e. spasticity, dystonia, choreoathetosis, or ataxia, which often occur in combination. In spastic CP, upper limb involvement varies from mild clumsiness in fine motor control to fixed muscle contractures preventing active extension of the elbow, wrist or fingers, or supination of the forearm (Manske 1990). Upper limb impairment in dyskinetic CP (dystonia or choreoathetosis) manifests as involuntary, uncontrolled, recurring, occasionally stereotyped movements (Surveillance of Cerebral Palsy in Europe 2000). Finally, ataxic CP is characterized by a loss of orderly muscular coordination and balance leading to movements of abnormal force, rhythm, and accuracy (Surveillance of Cerebral Palsy in Europe 2000).

The ability to reach, grasp, transport, and release objects is essential for performing activities of daily living, such as eating and grooming. In typically developing children the coordination of reaching develops over time as hand trajectories become smoother and less variable (Schneiberg, Sveistrup et al. 2002). Likewise, grasp and release require precise coordination and timing. Children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements (Steenbergen, Hulstijn et al. 1998) and difficulty with coordination of fingertip forces during grasp and release (Eliasson, Gordon et al. 1991; Eliasson and Gordon 2000).

We have recently developed the Reach & Grasp Cycle and reported upper limb kinematics for objective quantification of upper limb motor deficits in children with CP (Butler, Ladd et al. 2010a). In addition to joint kinematics, the duration, velocity, smoothness and trajectory of movement can provide important information regarding the quality of upper limb motion (Chang, Wu et al. 2005), and may help delineate the contribution of different etiologies and associated movement deficits that impair upper limb function in CP. Other studies have reported temporal-spatial parameters of reaching and/or grasping (Kuhtz-Buschbeck, Stolze et al. 1998; Chang, Wu et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Gordon, Keller et al. 2006; Coluccini, Maini et al. 2007; Rönnqvist and Rösblad 2007); however,
there remains no standardized protocol for three-dimensional upper limb motion (Jaspers, Desloovere et al. 2009). The Reach & Grasp Cycle is a sequence of tasks that incorporates the major joints of the upper limb and represents a functional task that is feasible yet challenging enough to reveal motor deficits. The purpose of the current research was to examine temporal-spatial characteristics of typically developing children and children with CP during the Reach & Grasp Cycle.

**Methods**

**Participants**

Thirty typically developing (TD) children and adolescents (14 males, 16 females, ages 5-18 years, mean age 10.9±4.1 years) participated in this study. Control participants had no history of orthopedic or neurological abnormalities. An additional 25 children with CP and upper limb involvement (9 males, 16 females, ages 5-18 years, mean age 12.3±3.7 years) also participated. Participants had to be able to follow verbal instructions and demonstrate sufficient grasping ability to complete the Reach & Grasp Cycle. Exclusion criteria included a history of upper extremity surgery, botulinum toxin injections to the upper extremity within six months, or use of anti-spasticity medications. Upper limb function was scored according to the Manual Ability Classification Scale (MACS) (Eliasson, Krumlinde-Sundholm et al. 2006). Demographics are listed in Table 4-1. The protocol was approved by the Stanford University Institutional Review Board. Informed consent was obtained from the children’s parent or guardian prior to testing; written assent was acquired from children 7 years and older.
Table 4-1: Total movement duration (seconds), movement efficiency as assessed by the index of curvature, and smoothness as measured by the number of movement units during the Reach & Grasp Cycle. Control (mean ± 1 SD) and individual patient data (average of two trials) are displayed with CP demographics.

**Typically Developing Participants (n=30)**

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age years</th>
<th>Time Cycle</th>
<th>Index of Curvature</th>
<th>Movement Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reach T₁ T₂ Return</td>
<td>Reach T₁ T₂ Return Total</td>
</tr>
<tr>
<td>Mean</td>
<td>14M</td>
<td>10.9</td>
<td>5.0 116 107 107 125</td>
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</tr>
<tr>
<td>SD</td>
<td>16F</td>
<td>4.1</td>
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**Participants with Cerebral Palsy (n=25)**

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<th>MACS</th>
<th>Sex</th>
<th>Age years</th>
<th>Time Cycle</th>
<th>Index of Curvature</th>
<th>Movement Units</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<td></td>
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<td>Reach T₁ T₂ Return Total</td>
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<td>I</td>
<td>M</td>
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<td>5.9</td>
<td>108 101 103 131</td>
<td>1 1 1 1 1 4</td>
</tr>
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<td>Spastic</td>
<td>I</td>
<td>F</td>
<td>14.3</td>
<td>5.2</td>
<td>112 102 101 141</td>
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<td>M</td>
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<td>Spastic</td>
<td>I</td>
<td>M</td>
<td>14.8</td>
<td>3.3</td>
<td>104 104 107 103</td>
<td>1 1 1 1 4</td>
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<td>110 108 104 124</td>
<td>1 1 1.5 2 5.5</td>
</tr>
<tr>
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<td>I</td>
<td>M</td>
<td>7.2</td>
<td>5.0</td>
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<td>II</td>
<td>M</td>
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<td>Spastic</td>
<td>II</td>
<td>F</td>
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<td>10.7</td>
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<td>4 1.5 5 3 13.5</td>
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<td>Spastic</td>
<td>II</td>
<td>F</td>
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<td>12.6</td>
<td>134 110 111 167</td>
<td>1.5 1 1 1.5 5</td>
</tr>
<tr>
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<td>Spastic</td>
<td>III</td>
<td>F</td>
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<td>10.6</td>
<td>154 109 106 153</td>
<td>2.5 2.5 1.5 4 10.5</td>
</tr>
<tr>
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<td>Dyskinetic</td>
<td>I</td>
<td>F</td>
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<td>5.6</td>
<td>114 106 102 139</td>
<td>1 1 1 1.5 4.5</td>
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<td>I</td>
<td>F</td>
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<td>5.0</td>
<td>116 105 104 114</td>
<td>2 1 1.5 1 5.5</td>
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<td>3 2 2 3 10</td>
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<td>2 1 2 2 6.5</td>
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<td>II</td>
<td>F</td>
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<td>8.3</td>
<td>150 108 110 131</td>
<td>3 1 2.5 3 9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>III</td>
<td>F</td>
<td>9.4</td>
<td>10.4</td>
<td>144</td>
<td>160</td>
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<tr>
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<td>Dyskinetic</td>
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<td>F</td>
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<td>144</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
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<td>III</td>
<td>M</td>
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<td>F</td>
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<td>160</td>
<td>120</td>
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<tr>
<td>16</td>
<td>L triplgia</td>
<td>Mixed (spastic &amp; dyskinetic)</td>
<td>III</td>
<td>F</td>
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<td>175</td>
<td>101</td>
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<tr>
<td>26</td>
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<td>Mixed (ataxic &amp; dyskinetic)</td>
<td>III</td>
<td>F</td>
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<td>17.9</td>
<td>309</td>
<td>338</td>
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<td>6</td>
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<td>Mixed (ataxic &amp; dyskinetic)</td>
<td>IV</td>
<td>F</td>
<td>7.0</td>
<td>18.6</td>
<td>1197</td>
<td>153</td>
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<tr>
<td><strong>Mean</strong></td>
<td>9 M</td>
<td><strong>12.3</strong></td>
<td><strong>8.5</strong>*</td>
<td><strong>187</strong>*</td>
<td><strong>121</strong></td>
<td><strong>121</strong></td>
<td><strong>173</strong>*</td>
<td><strong>4.9</strong>*</td>
</tr>
<tr>
<td><strong>SD</strong></td>
<td>16 F</td>
<td>3.7</td>
<td>4.3</td>
<td>215</td>
<td>48</td>
<td>40</td>
<td>106</td>
<td>14.0</td>
</tr>
</tbody>
</table>

* Statistically significant from typically developing participants with a P-value < .005 (Mann-Whitney-Wilcoxon rank sum test)

Abbreviations: $T_1, T_2 =$ first and second transport phase of the Reach & Grasp Cycle; M/F = male/female, MACS = Manual Ability Classification System level; R/L = right/left; n.d. = non-dominant hand
**Experimental Set-up**

Participants were seated comfortably at a height-adjustable table with the hips and knees flexed 90° and both feet on the ground. The arms rested on the table so that the shoulders were in a neutral position, the elbows were flexed approximately 90°, the forearms were pronated, and the wrists were held in neutral. Light-reflective markers were placed on the acromion process, lateral humeral condyle, and ulnar and radial styloid processes. A cylindrical cup (height: 12.5cm, diameter: 5.5cm) was placed at 75% of a participant’s maximum reach. From the start position, each participant was instructed to reach forward and grasp the cylinder, transport the cylinder to his/her mouth to simulate drinking ($T_1$), transport the cylinder back to its original location ($T_2$), release the cylinder, and return his/her arm to the start position. The TD participants were instructed to perform the task with their dominant hand; the children with CP were asked to perform the task with their less impaired hand and their more impaired hand. We asked the participants with CP to perform the task with their more impaired hand in order to assess the extent to which these participants deviated from the normal level of function. Three-dimensional position data were recorded during a Reach & Grasp Cycle, after 1-2 practice trials, using an eight-camera optoelectric motion capture system (Motion Analysis Corp., Santa Rosa, CA).

The phases of the Reach & Grasp Cycle were defined by the velocity of the wrist joint center, located at the midpoint between the ulnar and radial styloid processes. The onset of movement was identified as the first instant when the velocity of the wrist marker exceeded 5% of peak reaching velocity (van der Heide, Fock et al. 2005; Coluccini, Maini et al. 2007). The end of the Cycle was signified by a decrease in velocity to less than 5% of the maximum velocity upon returning the hand to the start position.

The temporal-spatial parameters were calculated to assess movement speed, strategy, efficiency, and smoothness. Temporal measures included total time to complete the task (Volman, Wijnroks et al. 2002; Chang, Wu et al. 2005; van der Heide, Fock et al. 2005; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007) and duration of each phase (Coluccini, Maini et al. 2007): reach, grasp, $T_1$, $T_2$, release, and
return. Total movement time was corrected for the amount of time each participant spent with the cylinder paused at his/her face. Spatial parameters included peak velocity of the wrist marker (Chang, Wu et al. 2005; van der Heide, Fock et al. 2005; Mackey, Walt et al. 2006), percent time to maximum velocity (Rand, Shimansky et al. 2000; Volman, Wijnroks et al. 2002), index of curvature (the distance the hand traveled divided by the linear distance between the start and stop position) (Kuhtz-Buschbeck, Stolze et al. 1998; van der Heide, Fock et al. 2005), and the number of movement units (the number of accelerations-decelerations in the velocity profile of the wrist marker) (Kuhtz-Buschbeck, Stolze et al. 1998; Volman, Wijnroks et al. 2002; Chang, Wu et al. 2005). Spatial parameters were calculated for the phases of reach, $T_1$, $T_2$, and return. The change in velocity between local maxima and minima in the velocity profile of the wrist marker had to exceed 40 mm/sec, or approximately 10-15% of peak velocity, to be considered a movement unit (Chang, Wu et al. 2005).

Statistical Analysis

To determine the influence of age on temporal-spatial parameters, Spearman’s rank correlation coefficients were computed between TD participant age and each parameter. Temporal-spatial values were calculated for reach, grasp, $T_1$, $T_2$, release, and return. Pair-wise comparisons were used to determine statistical differences for the object transport phases versus the non-transport phases (pairs: reach-$T_1$, reach-$T_2$, return-$T_1$, return-$T_2$). Significant differences between participants with CP and TD children were determined using the Mann-Whitney-Wilcoxon test. For the children with CP, Spearman’s rank correlation coefficients were computed to determine the correlation between MACS score and temporal-spatial parameters. An alpha level of .05 defined significant differences.

To assess repeatability of the temporal-spatial parameters, a representative subset of 12 TD children (5 males, 7 females, mean age: $10.7\pm4.1$ years) were tested twice, one week apart. On each occasion, children were asked to perform the Reach & Grasp Cycle three times. For each participant, the coefficient of variation (CV) was calculated as a measure of within-day and between-day repeatability. For within-day
CV, the mean and standard deviation from the three trials were used; for between-day CV, the mean and standard deviation from all six trials were used.

**Results**

*Typically Developing Children*

The total time to complete the Reach & Grasp Cycle was 5.0±1.1 seconds for TD participants. There were no correlations between age and any of the temporal measures after correcting for multiple comparisons. As shown in Figure 4-1A, the durations of the transport phases ($T_1, T_2$) were longer than the non-transport phases (*reach, return*) of the Reach & Grasp Cycle ($P \leq .001$). Grasp and release durations were shorter and more variable than the other phases ($P < .0001$): *grasp* ranged from 0.0-1.4 seconds and *release* ranged from 0.0-0.8 seconds (Figure 4-1B).

![Figure 4-1: Durations of (A) transport and non-transport phases of the Reach & Grasp Cycle, (B) Grasp and Release.](image)

The average peak hand velocities during the Reach & Grasp Cycle are displayed in Figure 4-2. Peak hand velocity, as well as linear distance traveled, was greater during the transport phases ($T_1, T_2$) than the non-transport phases (*reach, return*) ($P \leq .001$). Peak hand velocity occurred at 42% of *reach, 32% of $T_1, 43% of $T_2*, and 37% of *return*. There were no age differences in percent time to peak hand velocity or magnitude of peak hand velocity.
The efficiency of movement was assessed with the index of curvature, i.e. the total distance the hand traveled as a percentage of the linear distance between the start and stop positions. The index of curvature for all phases is listed in Table 4-1. There was a moderate negative correlation between age and the index of curvature during reach and return (rho=-.5298, p=.0408; rho=-.5436, p=.0318, respectively). The index of curvature was lower during the transport phases (T1, T2) than the non-transport phases (reach, return) (P≤.01).

The smoothness of movement was assessed with the number of movement units, i.e. the number of accelerations-decelerations in the velocity profile of the wrist marker. The number of movement units for all phases are listed in Table 4-1. There were no age differences in the number of movement units, and the number of movement units did not differ between the transport and non-transport phases.

**Repeatability**

Within-day and between-day measures of CV ranged from 0-.32 (Table 4-2), indicating low variability and good repeatability for all temporal-spatial parameters. Between-day CV values were slightly higher than within-day CV values as expected, though not statistically different.
Table 4-2: Relative variability of temporal-spatial parameters in a representative sample of 12 typically developing children (5 males, 7 females, mean age: 10.7±4.1 years). The within-day coefficient of variation (CV) represents the repeatability of three trials of the Reach & Grasp Cycle, and between-day CV represents the repeatability between two testing sessions, one week apart.

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<thead>
<tr>
<th></th>
<th>Within-Day CV</th>
<th>Between-Day CV</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Average</td>
<td>SD</td>
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<tr>
<td><strong>Duration (sec)</strong></td>
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<tr>
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<tr>
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</tr>
<tr>
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<tr>
<td>Return</td>
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<td>0.07</td>
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<tr>
<td>Total</td>
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<td><strong>Peak Velocity (mm/sec)</strong></td>
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<tr>
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<td>0.07</td>
</tr>
<tr>
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<td><strong>% Phase at Peak Velocity</strong></td>
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<td>Transport1</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Transport2</td>
<td>0.07</td>
<td>0.17</td>
</tr>
<tr>
<td>Return</td>
<td>0.32</td>
<td>0.19</td>
</tr>
<tr>
<td>Total</td>
<td>0.10</td>
<td>0.08</td>
</tr>
</tbody>
</table>

SD = standard deviation

Children with Cerebral Palsy

The total time to complete the Reach & Grasp Cycle for the children with hemiplegic CP was nearly twice as long as controls, 8.5±4.3 sec versus 5.0±1.1 sec (Z=4.07, \( P<.0001 \)). Grasp and release times were approximately five times longer than controls (Z=4.17, \( P<.0001 \) and Z=5.76, \( P<.0001 \), respectively) (Figure 4-1B). In contrast to control participants, no consistent patterns in phase duration emerged.
between the transport phases \((T_1, T_2)\) and non-transport phases \((reach, return)\) for children with CP.

The children with CP did not vary hand velocity between phases, proportional to distance traveled, as did controls (Figure 4-2). Percent time to peak velocity was 38% of reach, 28% of \(T_1\), 42% of \(T_2\), and 44% of return, similar to control values. However, percent phase to peak velocity among participants with CP was more variable, with values ranging from 10-89% across the four phases.

The children with CP demonstrated an increased index of curvature during reach and return relative to controls \((Z=3.83, P=.0001\) and \(Z=3.22, P=.0013\), respectively). For 21 of the 25 children with CP, the index of curvature was lower during the transport phases \((T_1, T_2)\) than the non-transport phases \((reach, return)\), indicating the trajectory of the hand was more direct while transporting the cylinder, similar to controls (Table 4-1). This was particularly true for CP Participant 6 with a diagnosis of ataxic CP and secondary hyperkinetic dystonia. Her index of curvature was ten times that of normal during reach and approximately five times the normal value during return, but was nearly within normal limits during \(T_1\) and \(T_2\). This patient demonstrated multiple attempts to complete the reach and return phases, whereas only one attempt was required to complete the transport phases. For the entire population of children with CP, the mean index of curvature was 187±215 for the reach phase and 173±106 for return. If Participant 6 is removed from the calculations, the mean index of curvature is reduced to 144±44 for the reach phase and 156±62 for the return phase; however, these values remain significantly greater than controls.

The total number of movement units was greater for the children with CP compared to controls \((Z=3.84, P=.0001)\), indicating less smooth movements (Table 4-1). Again, Participant 6 with ataxia had a markedly increased number of movement units during reach and return but demonstrated greatly improved movement smoothness during the transport phases. For the entire population of children with CP, the mean number of movement units was 4.9±14 for the reach phase and 2.9±2.9 for return \((Z=4.42, P<.0001\) and \(Z=3.36, P=.0008\), respectively). If the child with ataxia is removed from the calculations, the mean number of movement units is reduced to
2.1±1.2 for the *reach* phase and 2.5±1.7 for *return*; however, these values remain significantly greater than controls.

The total time to complete the Reach & Grasp Cycle (Spearman’s rho=.665, *P*<.0001), index of curvature during *reach* (rho=.656, *P*<.0001), and the total number of movement units (rho=.648, *P*<.0001) individually correlated strongly with MACS.

**Discussion**

The Reach & Grasp Cycle was developed for objective quantification of upper limb motion in children and offers a standardized protocol. Providing a functional context to a task has been shown to improve the quality of reaching movements in children with hemiparesis (Volman, Wijnroks et al. 2002). Thus, the Reach & Grasp Cycle reflects a functional activity, such as reaching for a cup and bringing it to the mouth. In addition to three-dimensional kinematics, temporal-spatial parameters provide important information regarding the quality of upper limb motion (Chang, Wu et al. 2005), and may help delineate the contribution of different movement deficits to functional impairment.

Temporal-spatial measures of movement time, peak velocity, and percent time to peak velocity did not differ with age among control participants, consistent with Kuhtz-Buschbeck et al. who examined a reach and grasp task in healthy children (1998). The number of movement units also did not differ with age. However, there was an increased index of curvature in the youngest children, suggesting that efficient hand trajectories require more mature motor control and coordination. Other studies have demonstrated that the coordination of reaching develops through the first decade of life, with hand trajectories becoming smoother and less variable with age (Kuhtz-Buschbeck, Stolze et al. 1998; Schneiberg, Sveistrup et al. 2002).

The percent time to peak velocity for all four phases (32-43%) was consistent with previous studies (Kuhtz-Buschbeck, Stolze et al. 1998; Chang, Wu et al. 2005). During the first transport phase (*T₁*), the percent time to peak velocity occurred at 32% of the phase compared to approximately 40% for the other phases, suggesting a more conservative control strategy when bringing an object to the mouth and targeting the
face. The children with CP were more variable in when they achieved peak velocity for each phase.

Despite the range and complexity of motion possible during unrestrained reaching movements, certain characteristic features exist in adults such as relatively straight hand paths and bell-shaped velocity profiles (Morasso 1981; Soechting and Lacquaniti 1981; Jeannerod 1984). Temporal-spatial parameters were relatively consistent among the 30 TD children, as evidenced by the small standard deviations shown in Figures 4-1, 4-2 and Table 4-1.

Differences between the transport and non-transport phases emerged. Among TD participants, phase durations and peak velocities were greater during the transport phases ($T_1$, $T_2$) versus the non-transport phases (reach, return). The hand moved a longer distance during the transport phases, resulting in the attainment of greater peak velocities, consistent with the concept of appropriate scaling of movement velocity to movement amplitude (Kuhtz-Buschbeck, Stolze et al. 1998). In general, the children with CP did not demonstrate this pattern, suggesting a more limited ability to modulate hand velocity. Control participants also demonstrated a decreased index of curvature during the transport phases versus non-transport phases (Table 4-1); this pattern was present in 21 of the 25 children with CP. In particular, the child with ataxic CP demonstrated a markedly improved index of curvature, decreased number of movement units, and substantially lower phase durations during the transport phases. This suggests that holding an object provided sensory feedback or weighting of the hand to improve performance.

Previous research shows that children with spastic CP take longer to perform reaching tasks than TD children (Mackey, Walt et al. 2006). Similarly, in the current study all participants with spastic CP, with the exception of Participants 14 and 19, had total movement times longer than mean TD values; Participants 1, 3, 15, and 22 had movement times more than two SD greater.

Children with dyskinetic CP have been found to exhibit slower movements during reaching (Sanger 2006). The majority of children with more severe dyskinesia, i.e. higher MACS level, (Participants 4, 7, 9, 10, and 11) had movement times that
were more than two SD longer than mean control values, and had longer movement times than those with less severe dyskinesia (Participants 2 and 12). Individuals with dyskinesia have difficulty performing sequential movements (Currá, Berardelli et al. 2000), which may explain the increased movement times required to complete the Reach & Grasp Cycle.

Cerebellar patients with ataxia have been shown to exhibit an increased variability in peak hand velocity and an increased grasp duration during reach-to-grasp movements (Rand, Shimansky et al. 2000). This was certainly true for Participant 6 with a primary diagnosis of ataxic CP, who introduced much of the variance in Figures 4-1 and 4-2, as well as Participant 26. During the reach phase Participant 6 made 10 attempts before grasping the cup, and both Participants 6 and 26 achieved highly variable peak velocities during each phase of the Reach & Grasp Cycle and had prolonged grasp and release durations.

The number of movement units has recently been shown to be a sensitive measure of the differences between spastic and normal reaching (Chang, Wu et al. 2005). In fact, nearly all children with CP in the current study demonstrated an increased number of movement units during the Reach & Grasp Cycle, regardless of movement disorder. Regarding movement efficiency, children with more severe dyskinetic CP tended to reach in a more curved path than those with less severe dyskinesia (Table 4-1), similar to Gordon et al. (Gordon, Keller et al. 2006).

The MACS score was highly correlated with the total time to complete the Reach & Grasp Cycle, the index of curvature during reach, and the total number of movement units, suggesting that the Reach & Grasp Cycle may be a valid, standardized protocol for measuring upper limb function. Although this study did not examine the temporal-spatial parameters of the less affected arm of children with CP, a similar study by Mackey et al. (Mackey, Walt et al. 2006), found no statistical differences in range of motion, timing, or peak angular velocity between the non-dominant and dominant arms in the control group and the dominant arm of control children compared to the unaffected arm of children with hemiplegia.
In summary, the consistent normative temporal-spatial data and the substantial differences that emerged between children with CP and controls reflect utility of the Reach & Grasp Cycle for quantitative evaluation of upper limb motor deficits. The Reach & Grasp Cycle offers a standardized protocol to measure upper limb function and may help delineate movement disorders associated with diagnoses of spastic, dyskinetic, and ataxic CP.
V. The Pediatric Upper Limb Motion Index: A comprehensive index of upper limb function during the Reach & Grasp Cycle

This research describes the development of a novel pediatric upper limb motion index (PULMI) for children with cerebral palsy (CP). The PULMI is based on upper limb kinematics and provides information regarding the quality of upper limb motion during the Reach & Grasp Cycle. We also report key temporal-spatial parameters for determining the quality of movement patterns in children with spastic, dyskinetic, and ataxic CP. Participants included 30 typically developing (TD) children (14 males, 16 females, age=10.9±4.1 years) for purposes of establishing a reference dataset, and 25 children with a diagnosis of cerebral palsy (CP) and upper limb involvement (9 males, 16 females, age=12.3±3.7 years) with varying levels of manual ability (Manual Ability Classification System, MACS levels I-IV). Upper limb kinematics and temporal-spatial parameters were collected for all participants during the Reach & Grasp Cycle. The root-mean-square difference was calculated between the data of each child with CP and the average from the TD population for eight kinematic variables over the Reach & Grasp Cycle, similar to the Gait Profile Score. The raw value was then scaled such that a score ≥100 indicated the absence of upper limb pathology, and every 10 points below 100 corresponded to one standard deviation away from the TD mean. By definition, the PULMI for the TD group was 100±10. The mean PULMI for the children with CP was 67±30 (range: 0-99), indicating a broad range of manual ability. The PULMI was significantly lower among the children with CP compared to the TD group (Wilcoxon Z=-5.06, p<.0001). There was a strong negative correlation between the PULMI and MACS for all children with CP, Spearman’s rho=-.78, p<.0001. PULMI scores were also significantly different between children with spastic CP and dyskinetic CP (Z=-2.47, p<.0135). All key temporal-spatial values were significantly different between the children with CP and the TD group: total movement time (Z=4.06, p<.0001), index of curvature during reach (Z=3.68, p=.0002), total number of movement units (Z=3.72, p=.0002), angular velocity of elbow extension during...
reach (Z=-3.96, \( p<.0001 \)), and the ratio of the peak velocities of the first transport phase and reach (Z=-2.48, \( p=.0129 \)). A logistic regression of four key temporal-spatial parameters correctly predicted 19 of 22 movement disorder sub-types (spastic versus dyskinetic CP). The PULMI and key temporal-spatial parameters of the Reach & Grasp Cycle offer a quantitative approach to analyzing the quality of upper limb function in children with CP.

**Introduction**

The ability to reach, grasp, transport, and release objects is central to activities of daily living, such as feeding and grooming. However, children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements (Steenbergen, Hulstijn et al. 1998) and the coordination of fingertip forces during grasp and release (Eliasson, Gordon et al. 1991; Eliasson and Gordon 2000). Movement deficits associated with CP include spasticity, dyskinesias (dystonia or athetosis), and ataxia (Surveillance of Cerebral Palsy in Europe 2000) and are thought to be associated with injury to specific brain regions. Spastic CP is characterized by muscle weakness, shortened muscle-tendon unit, a velocity-dependent and increased sensitivity to stretch, as well as a loss of selective motor control (Miller 2005). Dystonia is a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both (Sanger, Chen et al. 2010), while athetosis is defined as a slow, continuous, involuntary writhing movement that prevents maintenance of a stable posture (Sanger, Chen et al. 2010). Ataxia is a movement disorder that prevents the ability to generate a normal or expected voluntary movement trajectory that cannot be attributed to weakness or involuntary muscle activity (Sanger, Chen et al. 2006).

Motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function during gait in individuals with CP (Gage and Novacheck 2001; Mackey, Walt et al. 2005). Motion analysis of the upper limb is more technically challenging due to the non-cyclical nature of functional use and the increased range and complexity of motion at the shoulder joint (Rau, Dasselhorst-Klug et al. 2000). As a result, few researchers have
used motion analysis to characterize upper limb kinematics until recently (Mackey, Walt et al. 2005; Ricken, Bennett et al. 2005; van der Heide, Fock et al. 2005; Fitoussi, Diop et al. 2006; Mackey, Walt et al. 2006; Coluccini, Maini et al. 2007; Petuskey, Bagley et al. 2007; Jaspers, Feys et al. 2011). In addition to joint kinematics, the duration, velocity, smoothness and trajectory of movement can provide important information regarding the quality of upper limb motion (Chang, Wu et al. 2005; Butler, Ladd et al. 2010b), and may help delineate the contribution of different etiologies and associated movement deficits that impair upper limb function in CP, e.g. spasticity, dyskinesias, and ataxia. However, there remains no standardized protocol for reporting joint kinematics or temporal-spatial parameters based on 3-D upper limb motion (Jaspers, Desloovere et al. 2009; Kontaxis, Cutti et al. 2009). We have previously proposed the Reach & Grasp Cycle (Butler, Ladd et al. 2010a) to address this issue: the Reach & Grasp Cycle offers a standardized sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging enough to reveal key motor deficits in individuals with movement disorders.

The focus of this paper is the development of a comprehensive quantitative index of upper limb function based on three-dimensional kinematics, and the analysis of key temporal-spatial parameters during the Reach & Grasp Cycle. The Pediatric Upper Limb Motion Index (PULMI), based on upper limb kinematics during the Reach & Grasp Cycle, was developed to provide a comprehensive, quantitative index of upper limb movement quality. Similar measures have been developed for gait and proved useful for clinical and research applications, i.e. the Gait Deviation Index (GDI) and the Gait Profile Score (GPS) (Schwartz and Rozumalski 2008; Baker, McGinley et al. 2009). The PULMI can be used to quantify the overall severity of a neuromuscular deficit affecting upper limb performance and may be useful for monitoring a child’s progress over time or gauging the effect of a therapeutic or surgical intervention. The Pediatric Upper Limb Motion Index (PULMI) and key temporal-spatial parameters were designed to quantify differences in movement
patterns between typically developing children and children with CP and upper limb involvement, as well as between children with spastic, dyskinetic, and ataxic CP.

Methods

Participants

Thirty typically developing (TD) children (14 males, 16 females, ages 5-18 years, mean age 10.9±4.1 years) participated in this study. Control participants had no history of orthopedic or neurological abnormalities. An additional 25 children with CP and upper limb involvement (9 males, 16 females, ages 5-18 years, mean age 12.3±3.7 years) also participated. Movement disorder subtypes included spastic CP (n=13), dyskinetic CP (n=9), mixed spastic and dyskinetic CP (n=1), and mixed ataxic and dyskinetic CP (n=2), Table 5-1. All participants with dyskinetic or ataxic CP were diagnosed by a pediatric neurologist specializing in pediatric movement disorders. Participants with CP had to be able to follow verbal instructions and demonstrate sufficient grasping ability to complete the Reach & Grasp Cycle. Exclusion criteria included a history of upper extremity surgery, botulinum toxin injections to the upper extremity within the last six months, or current use of anti-spasticity medications.

Upper limb function was scored according to the Manual Ability Classification System (MACS) (Eliasson, Krumlinde-Sundholm et al. 2006). Demographics are listed in Table 5-1. The protocol was approved by the Stanford University Institutional Review Board. Informed consent was obtained from the children’s parent or guardian prior to testing; written assent was acquired from children 7 years and older.
Table 5-1: Participant demographics, PULMI scores, and key temporal-spatial measures during the Reach & Grasp Cycle.

<table>
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<tr>
<th>Typically Developing Children (n=30)</th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td>Age (years)</td>
<td>Sex</td>
<td>PULMI</td>
<td>Mvmt Time (sec)</td>
<td>IC Reach</td>
<td>Total NMU</td>
<td>Elbow Ext Angular Velocity (*/sec)</td>
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<td>10</td>
<td>1.07</td>
<td>13</td>
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<td>Primary Diagnosis</td>
<td>Movement Disorder</td>
<td>MACS Level</td>
<td>Age (years)</td>
<td>Sex</td>
<td>PULMI</td>
<td>Mvmt Time (sec)</td>
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<td>Spastic</td>
<td>I</td>
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<td>M</td>
<td>95.39</td>
<td>5.93</td>
</tr>
<tr>
<td>17</td>
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<td>5.82</td>
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45
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<td>4.34</td>
<td>214.78</td>
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PULMI = Pediatric Upper Limb Motion Index, Mvmt Time = total time to complete the Reach & Grasp Cycle, IC Reach = index of curvature during the reach phase, NMU = number of movement units, $T_1 = Transport \ 1$ phase of the Reach & Grasp Cycle, MACS = Manual Ability Classification Scale, R/L = Right or Left, n.d. = non-dominant hand, M/F = Male or Female.
**Experimental Set-up**

Participants were seated comfortably at a height-adjustable table with the hips and knees flexed 90° and both feet on the ground. The arms rested on the table so that the shoulders were in a neutral position, the elbows were flexed approximately 90°, the forearms were pronated, and the wrists were held in neutral. Light-reflective markers were placed on the upper limbs and trunk, as previously described (Butler, Ladd et al. 2010a). A cylindrical cup was placed at 75% of a participant’s maximum reach. From the start position, each participant was instructed to reach forward and grasp the cup, transport the cup to his/her mouth to simulate drinking ($T_1$), transport the cup back to its original location ($T_2$), release the cup, and return his/her arm to the start position. The TD participants were instructed to perform the task with their dominant hand; all TD participants were right hand dominant. The children with CP were asked to perform the task with their less impaired (dominant) hand first, followed by their more impaired (non-dominant) hand. Three-dimensional position data were recorded during the Reach & Grasp Cycle, after 1-2 practice trials, using an eight-camera optoelectric motion capture system (Motion Analysis Corp., Santa Rosa, CA).

**Data Analysis**

Upper limb joint kinematics were calculated for eight primary motions of the trunk and arm: trunk flexion/extension, trunk axial rotation, shoulder rotation, shoulder elevation, elbow flexion/extension, forearm pronation/supination, wrist flexion/extension, and wrist ulnar-radial deviation, as previously described (Butler, Ladd et al. 2010a). The root-mean-square (RMS) difference was calculated between a participant’s data and the mean from the reference dataset taken over all eight upper limb kinematic variables, for the entire Reach & Grasp Cycle, Figure 5-1, similar to the method applied to the lower limbs for gait, reported by Baker et al (2009). The average RMS difference for all upper limb kinematic variables represents the raw Pediatric Upper Limb Motion Index (PULMI_{raw}).
This RMS measure can be used in its raw format as a measure of upper limb pathology. However, to improve its interpretability the PULMI was scaled similar to the scaling of the Gait Deviation Index (Schwartz and Rozumalski 2008):

The raw PULMI score was computed for each subject in the control group ($PULMI_{\text{raw}}^k$, $k = 1, N_{\text{control}}$), and the sample mean and standard deviation of $PULMI_{\text{raw}}^k$ were calculated ($\text{Mean}(PULMI^{\text{TD}}_{\text{raw}})$, $\text{S.D.}(PULMI^{\text{TD}}_{\text{raw}})$). We computed the $z$-score with respect to the TD control for subject $a$,

$$zPULMI_{\text{raw}}^a = \frac{PULMI_{\text{raw}}^a - \text{Mean}(PULMI^{\text{TD}}_{\text{raw}})}{\text{S.D.}(PULMI^{\text{TD}}_{\text{raw}})}$$

We then multiplied these $z$-scores by 10 and subtracted them from 100 to give the PULMI for subject $a$,

$$PULMI^a = 100 - 10 * zPULMI_{\text{raw}}^a$$

Because the PULMI measures a scaled distance from the average TD motion, the resulting PULMI can be interpreted such that a PULMI $\geq 100$ indicates a subject whose upper limb motion is at least as close to the TD average as that of a randomly selected TD individual, i.e., a PULMI of 100 or higher indicates the absence of upper limb pathology. Every 10 points that the PULMI falls below 100 corresponds one standard deviation away from the TD mean.

**Figure 5-1:** The root-mean-square (RMS) difference, shaded, was calculated between a participant’s data (solid line) and the mean from the reference dataset (dashed line) for elbow flexion-extension.
A custom Matlab program (Mathworks, Natick, MA) was written to determine the phases of the Reach & Grasp Cycle using position data of the wrist joint center, i.e. the midpoint of markers placed on the ulnar and radial styloid processes, and a marker placed on the cup. Once the phases were determined, key temporal-spatial values were calculated, including: total time to complete the Reach & Grasp Cycle, index of curvature of the wrist during the reach phase (path length of the wrist during reach, divided by the linear distance between the initial and final positions), total number of movement units during the Reach & Grasp Cycle (number of acceleration-decelerations in the velocity profile of the wrist marker), angular velocity of elbow extension during reach, and a ratio of the peak velocities of the wrist during the first transport phase ($T_1$) and reach.

Qualitative Measures

The Manual Ability Classification System (MACS) level was determined for each child with CP. The MACS is a functional classification system that characterizes the extent to which an individual has limited hand and arm motor function (Eliasson, Krumlinde-Sundholm et al. 2006). The five levels of the MACS are based on the children's self-initiated ability to handle objects and their need for assistance or adaptation to perform manual activities in everyday life. Level I includes children with minor limitations; children with severe functional limitations are classified as Level IV or V.

Statistical Analysis

To assess reliability of the PULMI and key temporal-spatial parameters of the Reach & Grasp Cycle, at least two trials were recorded during the testing session for a representative subset of 12 TD children (5 males and 7 females, mean age: 10.7±4.1 years) and all children with CP. Intra-session reliability for the TD and CP groups are reported as the Spearman’s correlation coefficient for two trials.

Significant differences in PULMI scores and key temporal-spatial parameters between participants with CP and TD children, and between children with spastic and dyskinetic CP, were determined using the Mann-Whitney-Wilcoxon test.
The concurrent and face validity of the PULMI was evaluated by examining its behavior with respect to the MACS, an established overall pathology measure of upper limb function in children with CP. Spearman’s rank correlation coefficients were computed to determine the correlation between MACS level, PULMI, and key temporal-spatial parameters. An alpha level of .05 was used to define significant differences.

A multi-variable logistic regression was used to determine a linear combination of a priori temporal-spatial parameters to predict the movement abnormalities of spasticity or dyskinesia within the CP population.
Results

*Typically Developing Children*

The mean average RMS value for the TD group (raw PULMI score) was 9.18±1.94, with a median of 9.20. The symmetric distribution of raw PULMI scores for the TD group is displayed in Figure 5-2 a. By definition, the mean PULMI for the TD group was 100±10. The mean TD temporal-spatial parameters are in Table 5-1.

The intra-session reliability of PULMI scores and key temporal-spatial predictors for a representative subset of typically developing children (n=12) was high, as shown Table 5-2. PULMI values were strongly correlated from trial 1 to trial 2, with a Spearman’s correlation coefficient of .91. Similarly, the temporal-spatial predictors between trial 1 and trial 2 were strongly correlated (Spearman’s rho ≥ .69), with the exception of total number of movement units, with a correlation coefficient of .47, indicating a moderate correlation between values from trial 1 and trial 2.

<table>
<thead>
<tr>
<th></th>
<th>TD (n=12)</th>
<th>p-Value</th>
<th>CP (n=24)</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PULMI Score</td>
<td>.91</td>
<td>&lt;.0001</td>
<td>.96</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Movement Time</td>
<td>.89</td>
<td>.0001</td>
<td>.89</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>IC Reach</td>
<td>.80</td>
<td>.0016</td>
<td>.84</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Total No. Movement Units</td>
<td>.47</td>
<td>.1240</td>
<td>.84</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Elbow Extension Angular Velocity</td>
<td>.88</td>
<td>.0002</td>
<td>.80</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Peak Velocity: T1 + Reach</td>
<td>.69</td>
<td>.0126</td>
<td>.70</td>
<td>.0001</td>
</tr>
</tbody>
</table>

Table 5-2: Intra-session reliability of PULMI scores and *a priori* temporal-spatial predictors for a representative subset of typically developing children (TD, n=12) and the children with cerebral palsy (CP, n=24).
Figure 5-2: (a) Histogram of PULMI scores for all typically developing children (n=30). The mean average RMS value (PULMIraw) for the TD group was 9.18±1.94, with a median of 9.20, and (b) Histogram of PULMI scores for children with spastic CP (n=13) and dyskinetic CP (n=9).
**Children with Cerebral Palsy**

The mean PULMI for the children with CP was 67±30 (range: 0-99), indicating a broad range of manual ability. Profiles of RMS differences for all eight upper limb kinematic variables and the average RMS difference, i.e., raw PULMI score, are displayed in Figure 5-3 a,b for CP Participants 3 and 20 for demonstration purposes. Table 5-1 lists the scaled PULMI scores and key temporal-spatial parameters, as well as demographics, for all children with CP.

The intra-session reliability of PULMI scores and key temporal-spatial parameters for the children with CP was high, as displayed in Table 5-2. PULMI values were strongly correlated from trial 1 to trial 2, with a Spearman’s correlation coefficient of .96. Similarly, the temporal-spatial parameters demonstrated high intra-session reliability with correlations ranging from .70 to .89. In general, intra-session reliability was higher in the CP population than the TD population. Only one trial could be obtained from CP Participant 6; therefore, her data were excluded from the analysis of intra-session reliability.

The PULMI scores and all key temporal-spatial values were significantly different between the TD children and children with CP: PULMI score (Wilcoxon Z=-5.06, \( p<.0001 \)), total movement time (Z=4.06, \( p<.0001 \)), index of curvature during reach (Z=3.68, \( p=.0002 \)), total number of movement units (Z=3.72, \( p=.0002 \)), angular velocity of elbow extension during reach (Z=-3.96, \( p<.0001 \)), and the ratio of the peak velocities of the first transport phase and the reach phase (Z=-2.48, \( p=.0129 \)).

There was a strong negative correlation between the PULMI and MACS for all children with CP, Spearman’s rho=-.78, \( p<.0001 \).
Spastic, Dyskinetic, and Ataxic Cerebral Palsy

Figure 5-4 shows a scatter-plot of PULMI versus MACS levels I-IV for children with spastic CP (n=13), dyskinetic CP (n=9), mixed spastic and dyskinetic CP (n=1) and mixed ataxic and dyskinetic CP (n=2).

The PULMI scores were significantly lower among the children with dyskinetic CP versus spastic CP (Wilcoxon Z = -2.47, p = .0135) (Figure 5-2 b). There were no differences in the total movement time, index of curvature during reach, angular velocity of elbow extension during reach, or the ratio of the peak velocities of the first transport phase and the reach phase between the children with spastic CP and dyskinetic CP; however, the total number of movement units was significantly greater among the children with dyskinetic CP versus spastic CP (Z = 2.12, p = .0343).
The *a priori* predictors of spastic versus dyskinetic CP were total movement time to complete the Reach & Grasp Cycle, index of curvature during reach, total number of movement units, elbow extension angular velocity during reach, and the ratio of the peak velocities of the first transport phase and reach phase. When examined for colinearity, the *a priori* predictors were not redundant. Table 5-3 shows the Pearson’s inter-correlation coefficients of the predictors for both the TD and CP groups.

Using a logistic regression, a linear combination of four of the five *a priori* temporal-spatial parameters was determined:

\[ 10.23 + 0.54 \times MT + 0.048 \times IC \text{ Reach} - 0.60 \times NMU - 2.15 \times \text{Velo } T1/\text{Reach} \]

where MT = movement time, IC Reach = index of curvature during the *reach* phase, NMU = total number of movement units during the Reach & Grasp Cycle, and Velo T1/Reach = ratio of \( T_1 \) to *reach* peak velocities. The effect of angular velocity of
elbow extension during reach was not significant; thus, it was eliminated from the analysis. This linear combination of key temporal-spatial parameters correctly predicted 19 of 22, or 86% of movement disorder classifications of spastic versus dyskinetic types of CP, $\kappa=0.7$. The model incorrectly predicted the movement disorder of CP Participants 2, 15, and 27.

**Table 5-3**: Pearson’s inter-correlation coefficients of *a priori* temporal/spatial predictors for all typically developing children and children with spastic or dyskinetic cerebral palsy.

<table>
<thead>
<tr>
<th>Typically Developing Children (n=30)</th>
<th>Index of Curvature</th>
<th>Total NMU</th>
<th>Elbow Extension Angular Velocity</th>
<th>Peak Velocity: $T_1$ : Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement Time</td>
<td>0.04</td>
<td>0.18</td>
<td>-0.15</td>
<td>0.32</td>
</tr>
<tr>
<td>IC Reach</td>
<td>1.00</td>
<td>0.61</td>
<td>-0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Total NMU</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>Elbow Ext Angular Velocity</td>
<td>1.00</td>
<td>0.02</td>
<td>-0.40</td>
<td>0.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Children with Cerebral Palsy and Upper Limb Involvement (n=22)</th>
<th>Index of Curvature</th>
<th>Total NMU</th>
<th>Elbow Extension Angular Velocity</th>
<th>Peak Velocity: $T_1$ : Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement Time</td>
<td>0.42</td>
<td>0.75</td>
<td>-0.37</td>
<td>-0.47</td>
</tr>
<tr>
<td>IC Reach</td>
<td>1.00</td>
<td>0.47</td>
<td>-0.40</td>
<td>-0.49</td>
</tr>
<tr>
<td>Total NMU</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.31</td>
<td>-0.42</td>
</tr>
<tr>
<td>Elbow Ext Angular Velocity</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.04</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Although there were only two participants with ataxia (Participants 6 and 26), both participants exhibited a low PULMI score, long total movement times, high indices of curvature during reach, and an increased total number of movement units compared to the other children with CP. Participant 6 exhibited a greatly increased elbow extension angular velocity during the reach phase, while Participant 26 demonstrated a greatly increased ratio of $T_1$:Reach peak velocities, both with respect to the TD children and the participants with spastic and dyskinetic CP.


Discussion

The Pediatric Upper Limb Motion Index (PULMI) was developed for objective quantification of upper limb motion in children during the Reach & Grasp Cycle. In addition to the PULMI, key temporal-spatial parameters provide important information regarding the quality of upper limb motion to help delineate the contribution of different movement deficits to functional impairment.

The PULMI demonstrates strong face validity on the basis that it is derived from the RMS difference between upper limb kinematics for an individual child with CP and the average data from typically developing children. The TD group of 30 participants displayed a symmetric distribution of raw PULMI scores, i.e. RMS values; this combined with the closeness of the mean (9.18 degrees) and the median (9.20 degrees) suggests an adequate distribution from which to calculate PULMI scores in the CP population. Intra-session reliability of the PULMI was very high in both the TD and CP population (0.91 and 0.96, respectively), suggesting that it is also a very repeatable measure.

The strong correlation between the PULMI and the MACS (Spearman’s rho=-.78, p<.0001) provides further evidence of its validity. The MACS is a functional classification system that characterizes the extent to which an individual has limited hand and arm motor function; however, the MACS is not meant to be sensitive to changes after an intervention. The PULMI is based on three-dimensional kinematics of the upper limb, similar to the GDI and GPS for the lower limb during gait, and three-dimensional gait analysis is routinely used to evaluate treatment outcomes (Gage and Novacheck 2001). In addition, the differences between MACS levels are not necessarily equal, nor are children with CP equally distributed across the five levels, in contrast to the PULMI which has been scaled so that every 10 points below a score of 100 represents one standard deviation away from the TD mean. Thus, the PULMI offers a more quantitative and precise measure of upper limb function.

In general, intra-session reliability was higher among the children with CP than the TD group. Other studies have shown intra-session reliability of upper limb kinematics in children with CP to be high during reach, reach-to-grasp, and various
gross motor tasks (Mackey, Walt et al. 2005; Scheinberg, McKinley et al. 2010; Jaspers, Feys et al. 2011), though no comparison to TD children was made in these studies.

Another benefit of the PULMI is that the methods used to derive the PULMI allow for the visualization and interpretation of RMS differences in individual upper limb kinematic variables (Figure 5-3 a,b). These motion profiles provide useful insight into which variables contribute to an elevated raw PULMI score for a child with CP. For example, 5-3a suggests that wrist flexion-extension motion affects the quality of upper limb motion for CP Participant 3, while Figure 5-3b effectively demonstrates that deviations in elbow flexion-extension and pronation-supination primarily affect upper limb function in CP Participant 20.

There were significant differences in PULMI scores between the TD children and the children with CP. As expected, PULMI scores were lower among children with CP, indicating significant deviations in upper limb kinematics during the Reach & Grasp Cycle compared to controls.

Children with CP also demonstrated significant differences in all key temporal-spatial parameters from TD children, including a prolonged total movement time, in part due to prolonged grasp and release times (Butler, Ladd et al. 2010b), and an increased index of curvature during reach and an increased total number of movement units, indicating less efficient and less smooth movements. Among TD participants, peak velocities were greater during the first transport phases $T_1$ than the non-transport phase of reach, resulting in a greater ratio of peak velocities of the transport to non-transport phase (Table 5-1). The hand travels a longer distance during the transport phase, resulting in the attainment of greater peak velocities, consistent with the concept of appropriate scaling of movement velocity to movement amplitude (Kuhtz-Buschbeck, Stolze et al. 1998). In general, the children with CP did not demonstrate this pattern, as evidenced by the lower ratios of peak velocities. This suggests a more limited ability to modulate hand velocity among children with CP.

With the exception of Gordon et al. (2006), few studies have looked at the differences between spastic, dyskinetic, or ataxic CP, focusing rather on one particular
type of movement disorder. Our study is unique in that we have investigated the motor patterns of children with all three types of movement disorders.

Muscle contractures in the upper limbs are common in children with spastic CP, particularly at the elbow (Manske 1990), with elbow flexion contractures resulting in a reduced range of elbow extension. Spasticity at the elbow and elbow flexion contractures in participants with spastic CP likely contributed to a reduced angular velocity of elbow extension during reaching, as seen in Table 5-1 for participants 1, 3, 13, 15, 19, 21, 22, and 23. Patients with dyskinetic CP also demonstrated a reduced angular velocity of elbow extension, perhaps as a result of the finding that patients with dyskinesia have difficulty performing sequential movements (Currá, Berardelli et al. 2000).

Dystonia is a movement disorder caused by damage to the basal ganglia and thalamus (Bax, Tydeman et al. 2006), which results in involuntary sustained or intermittent muscle contractions that may cause twisting and repetitive movements, abnormal postures, or both (Sanger, Chen et al. 2010). During the Reach & Grasp Cycle, these involuntary movements may be characterized by an increased number of movement units and an increased index of curvature during the reach phase. Indeed, children with more severe dyskinetic CP tended to reach in a more curved path than those with less severe dyskinesia (Table 5-1), similar to findings reported by Gordon et al. (2006).

Children with dyskinetic CP had a significantly lower PULMI score than children with spastic CP, indicating more significant deviations in upper limb joint motions during the Reach & Grasp Cycle. Group differences may be secondary to the greater number of higher MACS levels in the group of children with dyskinetic CP. The small number of participants with dyskinesia available for testing limited our ability to control for level of upper limb function. However, this may be a representative sample of upper limb function for children with dyskinetic CP; Eliasson et al. (2006) report a higher MACS level (decreased upper limb function) for children with dyskinetic versus spastic CP. A logistic regression of 4 of the 5 a priori temporal-
spatial parameters correctly predicted 19 of 22 cases of spastic versus dyskinetic CP, indicating clear, quantitative differences between these two movement disorders.

Children with dyskinetic CP have been found to exhibit slower movements during reaching than typically developing children (Sanger 2006), and which may explain the increased movement times required to complete the Reach & Grasp Cycle found in the children with dyskinetic CP.

The number of movement units has been shown to be a sensitive measure of the differences between spastic and normal reaching (Chang, Wu et al. 2005). In fact, nearly all children with CP in the current study demonstrated an increased number of movement units during the Reach & Grasp Cycle, regardless of their movement disorder. However, the total number of movement units was significantly greater among the children with dyskinetic CP versus spastic CP ($Z=2.12, p = .0343$).

The cerebellum participates in the planning and coordination of movement; thus, cerebellar damage may result in an inability to judge distances accurately and is thought to cause intention tremor during voluntary movement (Kandel, Schwartz et al. 2000), as seen in patients with ataxic CP. Cerebellar patients with ataxia have been reported to exhibit an increased variability in peak hand velocity and an increased grasp duration during reach-to-grasp movements (Rand, Shimansky et al. 2000). Indeed, the two children with ataxia (CP Participants 6 and 26) demonstrated prolonged movement times (with increased grasp and release times), an increased index of curvature during reach, and a greater total number of movement units than any of the other children with spastic and/or dyskinetic CP. Participant 6 exhibited a greatly increased elbow extension angular velocity during the reach phase, while Participant 26 demonstrated a greatly increased ratio of $T_1$ to Reach peak velocities, with respect to the TD children and the participants with spastic and dyskinetic CP.

The current research provides strong evidence that the Pediatric Upper Limb Motion Index (PULMI) profile and key temporal-spatial parameters of the Reach & Grasp Cycle precisely quantify and delineate neuromotor abnormalities in spastic, dyskinetic, and ataxic CP. These measures have been shown to be valid and reliable, and thus are useful for both research and clinical applications.
VI. Conclusions

The objective of this dissertation was to develop a protocol for assessing upper limb motion in children with cerebral palsy (CP) and to evaluate it using three-dimensional motion analysis. Using a biomechanical model of the trunk and upper limbs, we calculated three-dimensional joint kinematics and temporal-spatial parameters for 30 typically developing (TD) children and 25 children with CP and upper limb involvement, ages 5-18 years. Consistent normative data and clinically significant differences in joint motions and temporal-spatial parameters between the CP and TD children suggest that the Reach & Grasp Cycle is a repeatable protocol for objective and quantitative evaluation of functional upper limb motor performance.

Next, we derived a single score of upper limb pathology from upper limb kinematics called the Pediatric Upper Limb Motion Index (PULMI). The root-mean-square difference was calculated between the data for each child with CP and the average from the TD population for eight kinematic variables over the Reach & Grasp Cycle. The PULMI was found to be significantly different between the TD children and children with CP (Wilcoxon Z=-5.06, \( p<.0001 \)), and between children with spastic CP and dyskinetic CP (Z=-2.47, \( p<.0135 \)). A logistic regression of four key temporal-spatial parameters correctly predicted 86% of movement disorder sub-types (spastic versus dyskinetic CP), \( \kappa=0.7 \). The PULMI was shown to correlate strongly with the standard manual ability classification system (MACS) for all children with CP (Spearman’s rho=-.78, \( p<.0001 \)), indicating the PULMI is a valid measure of upper limb function.

Contributions of this Dissertation

The methods for analyzing upper limb motion that were developed and evaluated in this dissertation address the need for a standardized protocol to assess quantitative measures of upper limb function in individuals with cerebral palsy. Upper limb involvement in CP can limit an individual’s ability to perform even basic activities of daily living, such as eating, drinking, and personal hygiene and may diminish their level of independence. Current methods for evaluating upper limb
deficits in these individuals are limited to subjective, observational assessments performed by a clinician, which are prone to high inter-rater variability and low measures of reliability. The rigorous methods applied to three-dimensional motion analysis of the upper limb provide a more objective measure of upper limb motion with improved reliability. Three-dimensional motion analysis of gait is considered the gold standard for evaluating lower limb function; it is our hope that the same will be true for evaluating upper limb function during the Reach & Grasp Cycle. The Reach & Grasp Cycle that we developed is similar in nature to the gait cycle, which should make it more acceptable to clinicians already accustomed to evaluating gait disorders based on three-dimensional motion analysis. The Reach & Grasp Cycle was developed to be feasible yet challenging for individuals with movement disorders. The required tasks include essential activities of daily living, including reaching, grasping, transporting an object to and from the mouth, targeting the mouth with the object and targeting the table with the object upon return, and releasing the object. The individual tasks, as well as the sequential nature of the tasks challenge the motor system.

Upper limb kinematics were collected for 30 typically developing children to ensure that the Reach & Grasp Cycle was a reliable protocol for objective and quantitative evaluation of upper limb performance. These motion curves are available online to the community as supplemental material for the article: Butler, E. E., A. L. Ladd, et al. (2010). "Three-dimensional kinematics of the upper limb during a Reach & Grasp Cycle for children." Gait & Posture 32: 72-77 (Chapter III of this dissertation). In addition, numerous temporal-spatial parameters were reported for our typically developing participants and participants with CP in the article: Butler, E. E., A. L. Ladd, et al. (2010b). "Temporal-spatial parameters of the upper limb during a Reach & Grasp Cycle for children." Gait & Posture 32: 301-306 (Chapter IV of this dissertation). These temporal-spatial parameters provide an enhanced picture of an individual’s performance during the Reach & Grasp Cycle: speed, efficiency, and smoothness of movement. A logistic regression of four key temporal-spatial parameters was shown to predict the movement disorder (spasticity versus dyskinesia) affecting an individual’s upper limb performance with 86% accuracy. Finally, the
Pediatric Upper Limb Motion Index (PULMI), described in Chapter V of this dissertation, provides a single score for quantifying the deviation in motion between an individual with CP and the control population. This score may be useful in both clinical and research applications.

Potential Applications

While it is challenging to characterize and quantify specific upper limb movement disorders in CP, it is essential for identifying the underlying neural correlates and etiology, assessing movement disorder subtypes, i.e. spasticity, dystonia, and ataxia, which affect treatment selection, monitoring an individual’s progress over time, and measuring treatment outcomes. The protocol developed here provides a framework for three-dimensional motion analysis of upper limb function during the Reach & Grasp Cycle. The quantitative outcome variables of upper limb kinematics, temporal-spatial parameters, and the PULMI score provide valuable information regarding the quality of upper limb movements during a functionally relevant task.

An improved understanding of the underlying neural correlates and etiology of CP and its associated movement disorders will improve our ability to treat individuals with CP. Most children with CP do not receive a specific prognosis or treatment plan until they present with motor deficits, e.g. delayed or abnormal gait. Early treatment, at an age where there is optimal neuronal plasticity, may improve a child’s motor control, prevent growth-related deformities, and reduce the need for surgical or pharmacological interventions at a later age. Previously we found that neonatal microstructural development of the posterior limbs of the internal capsule, as revealed on diffusion tensor imaging, correlates with the severity of gait and motor deficits at four years of age (Rose, Mirmiran et al. 2007). With improved quantitative analysis of upper limb function, as provided here in this dissertation, researchers may also be able to find a correlation between specific areas of the brain and severity of upper limb deficits. The goal is that these neural correlates would lead to the improved care and prognosis for children with CP.
In addition to research applications, the methods presented in this dissertation also have clinical applications. As previously mentioned, three-dimensional gait analysis is considered the gold standard for evaluating lower limb function in children with cerebral palsy. The results of gait analyses are used to monitor an individual’s progress over time, select the appropriate intervention, and assess objectively the outcome of the therapeutic or surgical interventions. The same could be true for three-dimensional analysis of the upper limb during the Reach & Grasp Cycle. In addition, the ability to quantitatively distinguish between different movement disorders is important for identifying the correct treatment. Spastic CP may be treated with surgical interventions, such as muscle lengthenings or transfers, while dyskinetic CP is a contra-indication for such procedures. Therefore, it is critical to distinguish the contribution of each movement disorder in order to provide the best care for these individuals.
Appendix: Matlab Code

Normalize upper limb kinematic data to 0-100% of the Reach & Grasp Cycle

% This program reads in UE data (.csv file from output of UETrak) for a % right Reach & Grasp Cycle. % The data are normalized to 101 data points, and output as a 101 x 8 matrix to a separate .csv file.

fid = -1;
msg = '';
while fid < 0
    disp(msg);
    filename = input('Enter file name: ', 's');
    [fid,msg] = fopen(filename);

% Read in data, extract the appropriate column of data, and normalize .to 101 data points

    Data = csvread(filename);

    Shoulder_Elev = interpolate(1, length(Data), Data(:,6), 100);
    Shoulder_IR = interpolate(1, length(Data), Data(:,7), 100);
    Elbow_Flex = interpolate(1, length(Data), Data(:,8), 100);
    Pronation = interpolate(1, length(Data), Data(:,37), 100);
    Wrist_Flexion = interpolate(1, length(Data), Data(:,38), 100);
    Wrist_Deviation = interpolate(1, length(Data), Data(:,39), 100);

Trunk_Fwd_Lean = interpolate(1, length(Data), Data(:, 20), 100);
Trunk_Lat_Lean = interpolate(1, length(Data), Data(:, 19), 100);
Trunk_Rotation = interpolate(1, length(Data), Data(:, 21), 100);

% Create matrix from individual column vectors and save to file
Matrix = [Shoulder_Elev Shoulder_IR Elbow_Flex Pronation
          Wrist_Flexion Wrist_Deviation Trunk_Fwd_Lean Trunk_Rotation];

newfile = input('Enter output file name (include .csv): ', 's');
csvwrite(newfile, Matrix)
end

Calculate joint angles at the point of task achievement
% Use this program after running data through an .m file to normalize kinematic data to 101 points and
% export as an 8-column csv file.
% This program calculates time points for the end of Reach, Transport 1, and Transport 2 based on elbow
% position and extracts the kinematic variables at each time point. The 40 extracted kinematic variables
%(5 time pts, 8 motions) are output on a single line for each subject whose file is in the given
directory.

clear all

directory=input('Type in the directory path of the .csv files:\n','s');
directory=strcat(directory,'\');
cd (directory);
filenames=dir('*\.csv');
no_of_csv_files=size(filenames,1)

for S=1:no_of_csv_files
    newfilename=filenames(S).name
    data=textread(newfilename,'%s','delimiter','\n');

    % open the .csv spreadsheet
    csvdata = dlmread(newfilename);

    % get kinematic data - numbers relate to the respective data columns
    shoulderElev = csvdata(:,1);
    shoulderRot = csvdata(:,2);
    elbowFlex = csvdata(:,3);
    proSup = csvdata(:,4);
    wristFlex = csvdata(:,5);
    wristDev = csvdata(:,6);
    trunkTilt = csvdata(:,7);
    trunkRot = csvdata(:,8);

    % calculate time points for end of Reach, Transport 1, and Transport 2 based on elbow position
    minElbowFlex1 = min(elbowFlex(1:50));
    indexMinElbowFlex1 = find(elbowFlex == minElbowFlex1);

    maxElbowFlex = max(elbowFlex);
    indexMaxElbowFlex = find(elbowFlex == maxElbowFlex);

    minElbowFlex2 = min(elbowFlex(51:101));
    indexMinElbowFlex2 = find(elbowFlex == minElbowFlex2);
% calculate variables

trunkTilt_0 = trunkTilt(1);
trunkTilt_R1 = trunkTilt(indexMinElbowFlex1);
trunkTilt_T1 = trunkTilt(indexMaxElbowFlex);
trunkTilt_T2 = trunkTilt(indexMinElbowFlex2);
trunkTilt_100 = trunkTilt(101);

trunkRot_0 = trunkRot(1);
trunkRot_R1 = trunkRot(indexMinElbowFlex1);
trunkRot_T1 = trunkRot(indexMaxElbowFlex);
trunkRot_T2 = trunkRot(indexMinElbowFlex2);
trunkRot_100 = trunkRot(101);

shoulderElev_0 = shoulderElev(1);
shoulderElev_R1 = shoulderElev(indexMinElbowFlex1);
shoulderElev_T1 = shoulderElev(indexMaxElbowFlex);
shoulderElev_T2 = shoulderElev(indexMinElbowFlex2);
shoulderElev_100 = shoulderElev(101);

shoulderRot_0 = shoulderRot(1);
shoulderRot_R1 = shoulderRot(indexMinElbowFlex1);
shoulderRot_T1 = shoulderRot(indexMaxElbowFlex);
shoulderRot_T2 = shoulderRot(indexMinElbowFlex2);
shoulderRot_100 = shoulderRot(101);

elevatorFlex_0 = elevatorFlex(1);
elevatorFlex_R1 = elevatorFlex(indexMinElbowFlex1);
elevatorFlex_T1 = elevatorFlex(indexMaxElbowFlex);
elevatorFlex_T2 = elevatorFlex(indexMinElbowFlex2);
elevatorFlex_100 = elevatorFlex(101);

proSup_0 = proSup(1);
proSup_R1 = proSup(indexMinElbowFlex1);
proSup_T1 = proSup(indexMaxElbowFlex);
proSup_T2 = proSup(indexMinElbowFlex2);
proSup_100 = proSup(101);

wristFlex_0 = wristFlex(1);
wristFlex_R1 = wristFlex(indexMinElbowFlex1);
wristFlex_T1 = wristFlex(indexMaxElbowFlex);
wristFlex_T2 = wristFlex(indexMinElbowFlex2);
wristFlex_100 = wristFlex(101);

wristDev_0 = wristDev(1);
wristDev_R1 = wristDev(indexMinElbowFlex1);
wristDev_T1 = wristDev(indexMaxElbowFlex);
wristDev_T2 = wristDev(indexMinElbowFlex2);
wristDev_100 = wristDev(101);

% Append calculated parameters to a .csv file,

outputfile = strcat(directory,'Repeatibility.csv');
fid = fopen(outputfile,'a');

fprintf(fid,'%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%
Plot upper limb kinematics with control data (mean ± 1SD)

% This program plots upper extremity patient data with normal data (mean +/- 1 SD).

clear
clc

% Read in Normal Data

EF_mean = csvread('EF_mean');
tmpx = csvread('tmpx');
tmpy = csvread('tmpy');

SE_mean = csvread('SE_mean');
tmpx2 = csvread('tmpx2');
tmpy2 = csvread('tmpy2');

SIR_mean = csvread('SIR_mean');
tmpx3 = csvread('tmpx3');
tmpy3 = csvread('tmpy3');

Pro_mean = csvread('Pro_mean');
tmpx4 = csvread('tmpx4');
tmpy4 = csvread('tmpy4');

WF_mean = csvread('WF_mean');
tmpx5 = csvread('tmpx5');
tmpy5 = csvread('tmpy5');

WD_mean = csvread('WD_mean');
tmpx6 = csvread('tmpx6');
tmpy6 = csvread('tmpy6');

TFL_mean = csvread('TFL_mean');
tmpx7 = csvread('tmpx7');
tmpy7 = csvread('tmpy7');

TR_mean = csvread('TR_mean');
tmpx8 = csvread('tmpx8');
tmpy8 = csvread('tmpy8');

% Read in Patient Information
cd('C:\Program Files\MATLAB_SV71\work\Upper Extremity\CP')

Patient_EF = csvread('EF_CP1.csv');
Patient_SE = csvread('SE_CP1.csv');
Patient_SIR = csvread('SIR_CP1.csv');
Patient_Pro = csvread('Pro_CP1.csv');
Patient_WF = csvread('WF_CP1.csv');
Patient_WD = csvread('WD_CP1.csv');
Patient_TFL = csvread('TFL_CP1.csv');
Patient_TR = csvread('TR_CP1.csv');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Make plots 1-8

x=[0:1:100]';

figure(1)

fill(tmpx, tmpy, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 20 140]);
plot(x, EF_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[20 ; 140], 'Color','k')
line([100 ; 100],[20 ; 140], 'Color','k')
line([18 ; 18],[0 ; 140], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[0 ; 140], 'Color', 'k', 'LineStyle', ':')
```matlab
line([85 ; 85],[0 ; 140], 'Color', 'k', 'LineStyle',':')
hold on

plot(x, Patient_EF , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Extension - Flexion')
title('Elbow Flexion/Extension')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2)

fill(tmpx2, tmpy2, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 0 120]);
plot(x, SE_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[0 ; 120], 'Color', 'k')
line([100 ; 100],[0 ; 120], 'Color', 'k')
line([18 ; 18],[0 ; 120], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[0 ; 120], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[0 ; 120], 'Color', 'k', 'LineStyle',':')
hold on

plot(x, Patient_SE , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Extension - Elevation')
title('Shoulder Elevation')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(3)

fill(tmpx3, tmpy3, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -50 50]);
```
plot(x, SIR_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-
')
line([0 ; 0],[-50 ; 50], 'Color', 'k')
line([100 ; 100],[-50 ; 50], 'Color', 'k')
line([18 ; 18],[-50 ; 50], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-50 ; 50], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-50 ; 50], 'Color', 'k', 'LineStyle',':')
hold on

plot(x, Patient_SIR , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('External - Internal')
title('Shoulder Rotation')

hold on

figure(4)
fill(tmpx4, tmpy4, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -20 100]);
plot(x, Pro_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-
')
line([0 ; 0],[-20 ; 100], 'Color', 'k')
line([100 ; 100],[-20 ; 100], 'Color', 'k')
line([18 ; 18],[-20 ; 100], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-20 ; 100], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-20 ; 100], 'Color', 'k', 'LineStyle',':')
hold on

plot(x, Patient_Pro , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Supination - Pronation')
title('Forearm Pronation/Supination')

.................................................................
figure(5)

fill(tmpx5, tmpy5, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -80 80]);
plot(x, WF_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[-80 ; 80], 'Color', 'k')
line([100 ; 100],[-80 ; 80], 'Color', 'k')
line([18 ; 18],[-80 ; 80], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-80 ; 80], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-80 ; 80], 'Color', 'k', 'LineStyle', ':')
hold on

plot(x, Patient_WF , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Extension - Flexion')
title('Wrist Flexion/Extension')

figure(6)

fill(tmpx6, tmpy6, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -20 20]);
plot(x, WD_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[-20 ; 20], 'Color', 'k')
line([100 ; 100],[-20 ; 20], 'Color', 'k')
line([18 ; 18],[-20 ; 20], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-20 ; 20], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-20 ; 20], 'Color', 'k', 'LineStyle', ':')
hold on

plot(x, Patient_WD , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Radial - Ulnar')
title('Wrist Deviation')

figure(7)
fill(tmpx7, tmpy7, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -10 50]);
plot(x, TFL_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[-10 ; 50], 'Color', 'k')
line([100 ; 100],[-10 ; 50], 'Color', 'k')
line([18 ; 18],[-10 ; 50], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-10 ; 50], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-10 ; 50], 'Color', 'k', 'LineStyle', ':')
hold on
plot(x, Patient_TFL , 'b--', 'LineWidth', 2)
xlabel('Percent of Reach & Grasp Cycle')
ylabel('Extension - Flexion')
title('Trunk Flexion/Extension')

figure(8)
fill(tmpx8, tmpy8, 'y', 'EdgeColor', [0.5 0.5 0.5]);
hold on
axis([0 100 -10 30]);
plot(x, TR_mean, 'Color', [0.5 0.5 0.5], 'LineStyle', '-')
line([0 ; 0],[-10 ; 30], 'Color', 'k')
line([100 ; 100],[-10 ; 30], 'Color', 'k')
line([18 ; 18],[-10 ; 30], 'Color', 'k', 'LineStyle', ':')
line([47.5 ; 47.5],[-10 ; 30], 'Color', 'k', 'LineStyle', ':')
line([85 ; 85],[-10 ; 30], 'Color', 'k', 'LineStyle', ':')
Determine phases of the Reach & Grasp Cycle and calculate temporal-spatial parameters

% This program will search a folder for all the temporal-spatial .ts files and open them for processing.
% The phases of the Reach & Grasp cycle are determined and movement times, peak velocities, indices of 
% curvature, and numbers of movement units are calculated for each phase.

directory=input('Type in the directory path of the temporal-spatial files:
','s');
directory=strcat(directory,'\');

filenames=dir('*.ts');
no_of_files=size(filenames,1)

% Thresholds
Tcup_v = 50; % Used to determine reach_end and release_end (initiation and end of mvmnts)
Tcup_p = 10; % Used to determine grasp_end and T2_end (cup z position)
Twrist_v = 20; % Used to determine reach_start, pause_end, and rtn_end
Tpause = 50; % Used to determine T1_end and pause_end (change in wrist speed during the pause)
Tframes = 50; % Used to determine T1_end

% Open each file
for S=1:no_of_files
    newfilename=filenames(S).name
    % Open the spreadsheet, ignore the headers, read in the appropriate columns for calculating phases
tsdata = dlmread(newfilename, '\t', 7, 0);

time = tsdata(:, 2);
cup_z = tsdata(:, 5);
cup_speed = tsdata(:, 9);
wrist_x = tsdata(:, 14);
wrist_y = tsdata(:, 15);
wrist_z = tsdata(:, 16);
wrist_speed = tsdata(:, 20);

% Calculate phases of Reach, Grasp, Transport 1, pause, Transport 2, Release, and Return
% Output is the vector index, e.g. if answer is first element of the vector '1' will be returned.
reach_start = find(wrist_speed > Twrist_v, 1);
reach_end = find(cup_speed(reach_start:end) > Tcup_v, 1) + reach_start - 1;

grasp_start = reach_end;
grasp_end = find((cup_z(grasp_start:end) - cup_z(1)) > Tcup_p, 1) + grasp_start - 1;
% Cup position greater than 'Tcup_p' of initial cup height
T1_start = grasp_end;
[cup_zMax cup_zMaxInd] = max(cup_z);
% Find magnitude and corresponding index of maximum cup height
T1_end = find((wrist_speed(cup_zMaxInd - Tframes:cup_zMaxInd + Tframes)) < Tpause, 1) +
cup_zMaxInd - Tframes + 1;
% Wrist speed must be less than 'Tpause' mm/sec; search 'Tframes' before and after max cup height
pause_start = T1_end;
pause_end_init = find(wrist_speed(pause_start:end) > (Twrist_v + Tpause), 1) + pause_start - 1;
[wrist_minVel pause_end] = min(wrist_speed(T1_end:pause_end_init));
pause_end = pause_end + pause_start - 1;
% Find minimum wrist speed between T1_end and when wrist speed is less than 'Twrist_v+Tpause'
mm/sec
T2_start = pause_end;
T2_end = find(cup_z(T2_start:end) < (cup_z(1) + Tcup_p), 1) + T2_start - 1;
% Cup position within 'Tcup_p' distance of initial cup height

release_start = T2_end;
release_end = find(cup_speed(release_start:end) < (wrist_speed(release_start:end) - Tcup_v), 1) + release_start - 1;
% Cup speed must be 'Tcup_v' mm/sec slower than wrist speed

rtn_start = release_end;
rtn_end = size(wrist_speed, 1);

% Calculate temporal parameters: total movement time (corrected for pause) and time of each phase.
% Correct for frame rate (100 fps)

reach = (reach_end - reach_start)*.01;
grasp = (grasp_end - grasp_start)*.01;
T1 = (T1_end - T1_start)*.01;
pause = (pause_end - pause_start)*.01;
T2 = (T2_end - T2_start)*.01;
release = (release_end - release_start)*.01;
rtn = (rtn_end - rtn_start)*.01;

mvmt_time = ((rtn_end - reach_start) - pause)*.01;

% Calculate spatial parameters:

% (1) Peak velocity of wrist marker and percent phase to peak velo during Reach, T1, T2, and Return

[peakVelo_reach indexPeakVelo_reach] = max(wrist_speed(reach_start:reach_end));
timePeakVelo_reach = (indexPeakVelo_reach*.01/reach)*100;
[peakVelo_T1 indexPeakVelo_T1] = max(wrist_speed(T1_start:T1_end));
timePeakVelo_T1 = (indexPeakVelo_T1/T1);

[peakVelo_T2 indexPeakVelo_T2] = max(wrist_speed(T2_start:T2_end));
timePeakVelo_T2 = (indexPeakVelo_T2/T2);

[peakVelo_rtn indexPeakVelo_rtn] = max(wrist_speed(rtn_start:rtn_end));
timePeakVelo_rtn = (indexPeakVelo_rtn/rtn);

% (2) Index of curvature during Reach, T1, T2, and Return
sum_ICReach = 0;
a = reach_end - reach_start;
for i=reach_start:a+reach_start-1
dist1 = sqrt((wrist_x(i+1)-wrist_x(i))^2+(wrist_y(i+1)-wrist_y(i))^2+(wrist_z(i+1)-wrist_z(i))^2);
    % add running tally to sum distance measures over entire phase
    sum_ICReach = sum_ICReach + dist1;
end
IC_reach = sum_ICReach/sqrt((wrist_x(a+reach_start)-wrist_x(reach_start))^2+(wrist_y(a+reach_start)-wrist_y(reach_start))^2+(wrist_z(a+reach_start)-wrist_z(reach_start))^2)*100;

sum_ICT1 = 0;
b = T1_end - T1_start;
for j=T1_start:b+T1_start-1
dist2 = sqrt((wrist_x(j+1)-wrist_x(j))^2+(wrist_y(j+1)-wrist_y(j))^2+(wrist_z(j+1)-wrist_z(j))^2);
    % add running tally to sum distance measures over entire phase
    sum_ICT1 = sum_ICT1 + dist2;
end
IC_T1 = \frac{\text{sum}_{ICT1}}{\sqrt{(\text{wrist}_x(b+T1\text{\_start}) - \text{wrist}_x(T1\text{\_start}))^2 + (\text{wrist}_y(b+T1\text{\_start}) - \text{wrist}_y(T1\text{\_start}))^2 + (\text{wrist}_z(b+T1\text{\_start}) - \text{wrist}_z(T1\text{\_start}))^2}}*100;

\text{sum}_{ICT2} = 0;
\text{c} = T2\text{\_end} - T2\text{\_start};
\text{for} \ k=T2\text{\_start}:c+T2\text{\_start}-1
\text{dist3} = \sqrt{(\text{wrist}_x(k+1) - \text{wrist}_x(k))^2 + (\text{wrist}_y(k+1) - \text{wrist}_y(k))^2 + (\text{wrist}_z(k+1) - \text{wrist}_z(k))^2};
\% \text{add running tally to sum distance measures over entire phase}
\text{sum}_{ICT2} = \text{sum}_{ICT2} + \text{dist3};
\text{end}

\text{IC}_T2 = \frac{\text{sum}_{ICT2}}{\sqrt{(\text{wrist}_x(c+T2\text{\_start}) - \text{wrist}_x(T2\text{\_start}))^2 + (\text{wrist}_y(c+T2\text{\_start}) - \text{wrist}_y(T2\text{\_start}))^2 + (\text{wrist}_z(c+T2\text{\_start}) - \text{wrist}_z(T2\text{\_start}))^2}}*100;

\text{sum}_{ICRtn} = 0;
\text{d} = rtn\text{\_end} - rtn\text{\_start};
\text{for} \ l=rtn\text{\_start}:d+rtn\text{\_start}-1
\text{dist4} = \sqrt{(\text{wrist}_x(l+1) - \text{wrist}_x(l))^2 + (\text{wrist}_y(l+1) - \text{wrist}_y(l))^2 + (\text{wrist}_z(l+1) - \text{wrist}_z(l))^2};
\% \text{add running tally to sum distance measures over entire phase}
\text{sum}_{ICRtn} = \text{sum}_{ICRtn} + \text{dist4};
\text{end}

\text{IC}_rtn = \frac{\text{sum}_{ICRtn}}{\sqrt{(\text{wrist}_x(d+rtn\text{\_start}) - \text{wrist}_x(rtn\text{\_start}))^2 + (\text{wrist}_y(d+rtn\text{\_start}) - \text{wrist}_y(rtn\text{\_start}))^2 + (\text{wrist}_z(d+rtn\text{\_start}) - \text{wrist}_z(rtn\text{\_start}))^2}}*100;

\% (3) Plot wrist speed, cup vertical position, cup speed, and add vertical lines for each phase

clf
plot(wrist_speed)
hold on
plot(cup_z, 'k')
hold on
```matlab
plot(cup_speed, 'r')
hold on

legend ('wrist speed', 'cup_z', 'cup speed')
y=[0:10:1000];
line(reach_start, y)
line(reach_end, y)
line(T1_start, y)
line(T1_end, y)
line(T2_start, y)
line(T2_end, y)
line(rtn_start, y)
line(rtn_end, y)
pause

% User counts the number of movement units for each phase and enters them at the prompt

NMU_reach=input('Enter number of movement units during reach: ');
NMU_T1=input('Enter number of movement units during T1: ');
NMU_T2=input('Enter number of movement units during T2: ');
NMU_rtn=input('Enter number of movement units during return: ');

NMU_total = NMU_reach + NMU_T1 + NMU_T2 + NMU_rtn;

% After the parameters have been calculated, append them to a .csv file
outputfile=strcat(directory,'TempSpat.csv')
fid = fopen(outputfile,'a');
fprintf(fid,'%s,%f,%f,%f,%f,%f,%f,',newfilename, reach, grasp, T1, T2, release, rtn, mvmt_time);
fprintf(fid,'%f,%f,%f,%f,',peakVelo_reach, peakVelo_T1, peakVelo_T2, peakVelo_rtn);
fprintf(fid,'%f,%f,%f,%f,',timePeakVelo_reach, timePeakVelo_T1, timePeakVelo_T2, timePeakVelo_rtn);
fprintf(fid,'%f,%f,%f,%f,%f,
\n',NMU_reach, NMU_T1, NMU_T2, NMU_rtn, NMU_total);
fclose(fid)
end```
Calculate peak elbow extension and elbow extension angular velocity in reach phase

% This program does a batch-processing to calculate the peak elbow extension and elbow extension angular velocity in Reach phase.

clear
clc

% Read in Patient Data

directory=input('Type in the directory path of the .csv files:\n','s');
directory=strcat(directory,'\');
cd (directory);

filenames=dir('*\.csv');
no_of_csv_files=size(filenames,1)

for S=1:no_of_csv_files
    newfilename=filenames(S).name
    Data = dlmread(newfilename);
    EF = Data(:,8); % right elbow flex/extension

    % Calculate the Reach phase
    % Output is the vector index, e.g. if answer is first element of the vector then '1' will be returned.
    [EF_max EF_maxInd] = max(EF); % peak elbow flexion
    [EF_min1 EF_min1Ind] = min(EF(1:EF_maxInd)); % peak elbow ext in Reach
    reach_start = 1;
reach_end = EF_min1Ind;
reach = (reach_end - reach_start)*.01;
EF_velo = (EF(1) - EF_min1)/reach;
% elbow extension angular velocity in Reach

% Append calculated parameters to a .csv file,
outputfile = strcat(directory,'TD_EF.csv');
fid = fopen(outputfile,'a');
fprintf(fid,'%s,%f,%f,
',newfilename, EF_min1, EF_velo);
fclose(fid);
end

Calculate RMS difference between a participant with CP and mean TD data

% This program does a batch-processing to calculate the RMS difference between an individual with cerebral
% palsy and the mean normal data

clear
clc

% Read in Normal Data
EF_mean = csvread('EF_mean');
SE_mean = csvread('SE_mean');
SIR_mean = csvread('SIR_mean');
Pro_mean = csvread('Pro_mean');

WF_mean = csvread('WF_mean');

WD_mean = csvread('WD_mean');

TFL_mean = csvread('TFL_mean');

TR_mean = csvread('TR_mean');

% Read in Patient Data

directory=input('Type in the directory path of the .csv files:
','s');
directory=strcat(directory,'\n','s');
cd (directory);

filenames=dir('*.csv');
no_of_csv_files=size(filenames,1)

for S=1:no_of_csv_files
    newfilename=filenames(S).name
    Data = dlmread(newfilename);
    SE = Data(:,1);
    SIR = Data(:,2);
    EF = Data(:,3);
    Pro = Data(:,4);
    WF = Data(:,5);
    WD = Data(:,6);
    TFL = Data(:,7);
    TR = Data(:,8);
% Calculate absolute difference between the patient data vector and the mean data vector
    SE_diff = abs(SE_mean - SE);
    SIR_diff = abs(SIR_mean - SIR);
    EF_diff = abs(EF_mean - EF);
    Pro_diff = abs(Pro_mean - Pro);
    WF_diff = abs(WF_mean - WF);
    WD_diff = abs(WD_mean - WD);
    TFL_diff = abs(TFL_mean - TFL);
    TR_diff = abs(TR_mean - TR);

% Calculate RMS difference: RMS = Euclidean length/sqrt(number of elements in vector)
    n = 101;     % 101 elements in vector
    SE_rms = norm(SE_diff)/sqrt(n);
    SIR_rms = norm(SIR_diff)/sqrt(n);
    EF_rms = norm(EF_diff)/sqrt(n);
    Pro_rms = norm(Pro_diff)/sqrt(n);
    WF_rms = norm(WF_diff)/sqrt(n);
    WD_rms = norm(WD_diff)/sqrt(n);
    TFL_rms = norm(TFL_diff)/sqrt(n);
    TR_rms = norm(TR_diff)/sqrt(n);
    Average_rms =  (SE_rms+SIR_rms+EF_rms+Pro_rms+WF_rms+WD_rms+TFL_rms+TR_rms)/8;

% Append calculated parameters to a .csv file,
    outputfile = strcat(directory,'CP_rms.csv');
    fid = fopen(outputfile,'a');

    fprintf(fid,'%s,%f,%f,%f,%f,%f,%f,\n',newfilename, SE_rms, SIR_rms, EF_rms, Pro_rms, WF_rms);
    fprintf(fid,'%f,%f,%f,%f,%f,\n',WD_rms, TFL_rms, TR_rms, Average_rms);

    fclose(fid);
end
References


