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The Pediatric Upper Limb Motion Index and a Temporal-Spatial Logistic Regression: Quantitative Analysis of Upper Limb Movement Disorders during the Reach & Grasp Cycle

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Abstract

This study describes a novel pediatric upper limb motion index (PULMI) for children with cerebral palsy (CP). The PULMI is based on three-dimensional kinematics and provides quantitative information of upper limb motion during the Reach & Grasp Cycle. We also report key temporal-spatial parameters for children with spastic, dyskinetic, and ataxic CP. Participants included 30 typically-developing (TD) children (age=10.9±4.1 years) and 25 children with CP and upper limb involvement (age=12.3±3.7 years), Manual Ability Classification System (MACS) levels I-IV. The PULMI is calculated from the root-mean-square difference for eight kinematic variables between each child with CP and the average TD values, and scaled such that the TD PULMI is 100±10. The PULMI was significantly lower among children with CP compared to TD children (Wilcoxon $Z=-5.06$, $p<.0001$). PULMI scores were significantly lower among children with dyskinetic CP compared to spastic CP ($Z=-2.47$, $p<.0135$). There was a strong negative correlation between PULMI and MACS among children with CP (Spearman's $\rho=-.78$, $p<.0001$). Temporal-spatial values were significantly different between CP and TD children: movement time ($Z=4.06$, $p<.0001$), index of curvature during *reach* ($Z=3.68$, $p=.0002$), number of movement units ($Z=3.72$, $p=.0002$), angular velocity of elbow extension during *reach* ($Z=-3.96$, $p<.0001$), and *transport*:*reach* peak velocities ($Z=-2.48$, $p=.0129$). A logistic regression of four temporal-spatial parameters, the Pediatric Upper Limb Temporal-Spatial Equation (PULTSE), correctly predicted 19/22 movement disorder subtypes (spastic versus dyskinetic CP). The PULMI, PULTSE, and key temporal-spatial parameters of the Reach & Grasp Cycle offer a quantitative approach to analyzing upper limb function in children with CP.

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Conflict of Interest Statement

The authors have no financial or personal relationships with other people or organizations that could have inappropriately influenced or biased their work.

Keywords

Three-dimensional kinematics; upper limb; children; cerebral palsy

Introduction

The ability to reach, grasp, transport, and release objects is central to many activities of daily living. However, children with cerebral palsy (CP) often have difficulty with the timing and coordination of reaching movements (Steenbergen et al. 1998) and the coordination of fingertip forces during grasp and release (Eliasson and Gordon 2000; Eliasson et al. 1991). The Surveillance of Cerebral Palsy in Europe (Surveillance of Cerebral Palsy in Europe 2000) classifies CP into the following subtypes: spastic, dyskinetic, and ataxic CP. Spastic CP is characterized by spasticity, muscle weakness, shortened muscle-tendon unit, and loss of selective motor control (Rose 2009; Rose and McGill 2005). Dyskinetic CP may be dystonic or athetotic: dystonia is a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both (Sanger et al. 2010), whereas athetosis is defined as slow, continuous, involuntary writhing movements that prevent maintenance of a stable posture (Sanger et al. 2010). Ataxic CP is characterized by an inability to generate a normal or expected voluntary movement trajectory that cannot be attributed to weakness or involuntary muscle activity (Sanger et al. 2006). The CP subtype affects not only the quality of movement, but it is also relevant for determining the most appropriate treatment. Children with CP may present with more than one type of movement disorder; in such cases, these patients are often classified by the predominant movement disorder with listing of secondary disorders (Bax et al. 2005; Sanger et al. 2003).

Motion analysis offers an objective method for quantifying movement and is considered the gold standard for evaluating lower limb function in individuals with CP during gait (Gage and Novacheck 2001; Mackey et al. 2005). Various measures that provide a single score to quantify the overall severity of gait pathology have been developed, e.g. the Gillette Gait Index (Schutte et al. 2000), the Gait Deviation Index (Schwartz and Rozumalski 2008), and the Gait Profile Score (Baker et al. 2009). Upper limb motion analysis 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 et al. 2000). Thus, few researchers have used motion analysis to characterize upper limb kinematics, until recently (Coluccini et al. 2007; Fitoussi et al. 2006; Jaspers et al. 2011; Mackey et al. 2005; Mackey et al. 2006; Petuskey et al. 2007; Ricken et al. 2005; van der Heide et al. 2005), and even fewer indexes of overall upper limb movement pathology have been proposed (Jaspers et al. 2011; Riad et al. 2011).

In addition to joint kinematics, temporal-spatial parameters such as duration, velocity, smoothness and trajectory of movement can provide important quantitative information about the quality of upper limb motion (Butler et al. 2010b; Chang et al. 2005), and may help delineate the contribution of different etiologies and associated movement deficits that impair upper limb function in CP. However, there remains no standardized protocol for

reporting joint kinematics or temporal-spatial parameters based on three-dimensional upper limb motion (Jaspers et al. 2009; Kontaxis et al. 2009). We have proposed the Reach & Grasp Cycle (Butler et al. 2010a) to address these issues. 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.

The purpose of this research was threefold: (1) to develop a quantitative index of upper limb function based on three-dimensional kinematics, the Pediatric Upper Limb Motion Index (PULMI), (2) to examine key temporal-spatial parameters during the Reach & Grasp Cycle, and (3) to construct a linear combination of temporal-spatial parameters, the Pediatric Upper Limb Temporal-Spatial Equation (PULTSE), that distinguishes between spastic and dyskinetic movement disorders. The PULMI can be used to quantify the severity of neuromuscular deficits affecting upper limb performance and may be useful for monitoring a child's progress over time or gauging the effects of therapeutic or surgical interventions. Temporal-spatial parameters were selected and analyzed to quantify differences in movement patterns between CP and TD children, as well as between children with spastic, dyskinetic, and ataxic CP. In conjunction, the identification and delineation of different movement disorders is central to determining appropriate treatments and evaluating outcomes in children with CP.

Methods

Participants

Participants included 30 typically developing (TD) children (14 males, 16 females, ages 5–18 years, mean=10.9±4.1 years) with 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=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 1). A pediatric neurologist specializing in movement disorders classified the movement disorders of all participants with CP. Eligible participants had 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 current use of anti-spasticity medications. Upper limb function was scored according to the Manual Ability Classification System (MACS) (Eliasson et al. 2006).

The protocol was approved by the Stanford University Institutional Review Board. Informed consent was obtained from each child's parent/guardian prior to testing; written assent was acquired from children 7 years and older.

Experimental Set-up

Participants were seated at a height-adjustable table with hips and knees flexed 90° and both feet on the ground. The arms rested on the table with shoulders in a neutral position, elbows flexed approximately 90°, forearms pronated, and wrists in neutral. Light-reflective markers

were placed on the upper limbs and trunk, as previously described (Butler et al. 2010a). A cylindrical cup was placed at 75% of maximum reach. From the *start* position, each participant was instructed to *reach* forward and *grasp* the cup, *transport* the cup to his/her mouth (T_1), *transport* the cup back to its original location (T_2), *release* the cup, and *return* to the start position. The TD participants performed the task with their dominant hand; all TD participants were right-hand dominant. The children with CP performed the task with the less impaired (dominant) hand first, followed by the 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).

Pediatric Upper Limb Motion Index (PULMI)

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 et al. 2010a), and a reference dataset was established from the kinematic data of the 30 TD children. The root-mean-square (RMS) difference was calculated between a participant's data and the mean from the reference dataset for all eight upper limb kinematic variables, over the Reach & Grasp Cycle (Figure 1), similar to the method applied to gait by Baker *et al.* (2009). The average RMS difference for all upper limb kinematic variables represents the raw PULMI score ($PULMI_{raw}$) and reflects upper limb movement pathology. To improve interpretability, the PULMI was scaled similar to the Gait Deviation Index (Schwartz and Rozumalski 2008):

The raw PULMI score was computed for each subject in the TD control group ($PULMI_{raw}^k$; $k=1, N_{control}$), and the group mean and standard deviation of $PULMI_{raw}^k$ were calculated ($Mean(PULMI_{raw}^{TD})$, $S.D.(PULMI_{raw}^{TD})$). The z -score was computed with respect to the TD group for participant a , as shown in Equation 1:

$$zPULMI_{raw}^a = \frac{PULMI_{raw}^a - Mean(PULMI_{raw}^{TD})}{S.D.(PULMI_{raw}^{TD})} \quad \text{Equation 1}$$

The z -score was then multiplied by 10 and subtracted from 100 to give the PULMI for participant a :

$$PULMI^a = 100 - 10 * zPULMI_{raw}^a \quad \text{Equation 2}$$

Because the PULMI measures a scaled distance from the average TD motion (Equation 2), the resulting PULMI can be interpreted as follows:

- Every 10 points that the PULMI falls below 100 corresponds to one standard deviation below the TD mean.

- A PULMI score > 100 indicates that the participant's upper limb motion is at least as close to the TD average as that of a randomly selected TD individual, i.e., upper limb motion is within normal limits.

Temporal-Spatial Parameters and Pediatric Upper Limb Temporal-Spatial Equation (PULTSE)

A custom program was written in Matlab (Mathworks, Natick, MA) to determine the phases of the Reach & Grasp Cycle using position data of the wrist joint center, i.e., midpoint of markers placed on the ulnar and radial styloid processes, and a marker on the cup. Once the phases were determined, five key temporal-spatial values were calculated: total time to complete the Reach & Grasp Cycle (MT), index of curvature of the wrist during *reach* phase (IC *reach*: 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 (NMU: number of acceleration-decelerations in the velocity profile of the wrist marker), angular velocity of elbow extension during *reach* (ElbowExt *reach*), and a ratio of the peak velocities of the wrist during the first transport phase (T_1) and *reach* (Velo T_1 /*reach*). To predict the presence of a spastic versus dyskinetic movement disorder, a multivariable logistic regression was used to construct a linear combination of these temporal-spatial parameters, named the Pediatric Upper Limb Temporal-Spatial Equation (PULTSE).

Qualitative Measures

The Manual Ability Classification System (MACS), an established functional classification system that characterizes the extent to which an individual has limited hand and arm motor function (Eliasson et al. 2006), was determined for each child with CP. The five levels of the MACS reflect a child's self-initiated ability to handle objects and their need for assistance to perform manual activities in everyday life. Level I reflects minor limitations, whereas more 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 for a representative subset of 12 TD children (5 males, 7 females, age=10.7±4.1 years) and the children with CP. Intra198 session reliability for the TD and CP groups were reported as the Spearman's correlation coefficient for two trials.

Significant differences in PULMI scores and temporal-spatial parameters between CP and TD participants, and between children with spastic and dyskinetic CP, were determined using the Mann-Whitney-Wilcoxon test.

The concurrent validity of the PULMI was evaluated with respect to the MACS. Spearman's rank correlation coefficients were computed between MACS level, PULMI, and key temporal-spatial parameters. An alpha level of .05 was used to define significant differences.

A multivariable logistic regression was used to determine the PULTSE, a linear combination of *a priori* temporal-spatial parameters.

Results

Typically Developing Children

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

The intra-session reliability of PULMI scores and temporal-spatial predictors for a representative subset of TD children was high (Table 2). PULMI values were strongly correlated from trial 1 to trial 2 (Spearman's $\rho = .91$). Similarly, the temporal-spatial predictors between trial 1 and trial 2 were strongly correlated (Spearman's $\rho = .69$), with the exception of NMU (Spearman's $\rho = .47$), indicating a moderate correlation between trial 1 and trial 2.

Children with Cerebral Palsy

The mean PULMI for children with CP was 67 ± 30 (range: 0–99), indicating a broad range of manual ability. For demonstration purposes, RMS profiles of all eight upper limb kinematic variables and the average RMS difference, $PULMI_{raw}$, are displayed in Figure 3a,b for CP Participants 3 and 20. Table 1 lists the scaled PULMI scores and temporal-spatial values for children with CP.

The intra-session reliability of PULMI scores and key temporal-spatial parameters for children with CP was high (Table 2). PULMI values were strongly correlated from trial 1 to trial 2 (Spearman's $\rho = .96$). Similarly, the temporal-spatial parameters demonstrated high intra-session reliability ($\rho = .70$ – $.89$). Intra-session reliability was generally higher among the CP population than the TD population. Only one trial was obtained from CP Participant 6; therefore, her data were excluded from this analysis.

The PULMI scores and all key temporal-spatial values were significantly different between the CP and TD children: PULMI score (Wilcoxon $Z = -5.06$, $p < .0001$), MT ($Z = 4.06$, $p < .0001$), IC *reach* ($Z = 3.68$, $p = .0002$), NMU ($Z = 3.72$, $p = .0002$), ElbowExt *reach* ($Z = -3.96$, $p < .0001$), and Velo $T_I/reach$ ($Z = -2.48$, $p = .0129$).

There was a strong negative correlation between the PULMI and MACS for all children with CP ($\rho = -.78$, $p < .0001$).

Cerebral Palsy Movement Disorder Subtypes

Figure 4 displays PULMI score versus MACS level for children with varying CP subtypes. The PULMI scores were significantly lower among children with dyskinetic CP versus spastic CP (Wilcoxon $Z = -2.47$, $p = .0135$) (Figure 2b).

There were no differences in MT, IC *reach*, ElbowExt *reach*, or Velo $T_I/reach$ between the children with spastic and dyskinetic CP; however, NMU was significantly greater among the children with dyskinetic versus spastic CP ($Z = 2.12$, $p = .0343$).

The *a priori* predictors of spastic versus dyskinetic CP were MT, IC *reach*, ElbowExt *reach*, Velo T_1 /*reach*, and NMU. When examined for collinearity, the *a priori* predictors were not redundant, as evidenced by the Pearson's inter-correlation coefficients for the TD and CP groups in Table 3. Using a logistic regression, a linear combination of four of five *a priori* temporal-spatial parameters was determined:

$$10.23 + [0.54 * MT] + [-0.048 * IC \text{ reach}] + [-0.60 * NMU] + [-2.15 * Velo \ T_1 / \text{reach}]$$

Equation 3

The effect of elbow extension angular velocity during *reach* was not significant and was eliminated from the analysis. The PULTSE (Equation 3) correctly predicted 19 of 22, or 86%, of spastic versus dyskinetic CP classifications, $\kappa=0.7$. The model incorrectly predicted the movement disorder of CP Participants 2, 15, and 27.

Although there were only two participants with ataxia (Participants 6 and 26), both participants exhibited a low PULMI score, long MT, high IC *reach*, and an increased NMU compared to the other children with CP. Participant 6 exhibited a greatly increased elbow extension angular velocity during *reach*, while Participant 26 demonstrated a greatly increased ratio of T_1 :*reach* peak velocities, with respect to the TD children and the participants with spastic and/or dyskinetic CP.

Discussion

The Pediatric Upper Limb Motion Index (PULMI) was developed for objective quantification of upper limb motion during the Reach & Grasp Cycle. Key temporal spatial parameters and the Pediatric Upper Limb Temporal-Spatial Equation (PULTSE) provide additional information to help delineate the contribution of different movement disorders.

The PULMI demonstrates strong face validity as it is derived from the RMS difference between upper limb kinematics for an individual with CP and the average from TD children. The symmetric distribution of raw TD PULMI scores and the proximity of the mean (9.18°) and median (9.20°) suggest an adequate distribution from which to calculate PULMI scores. Intra-session reliability of the PULMI was high in both the TD and CP population (0.91 and 0.96, respectively), suggesting excellent repeatability. Furthermore, previous research shows that mean intra-session and inter-session errors in upper limb kinematics ranged from 0.6°–3.4° and 1.6°–4.8°, respectively (Butler et al. 2010a), confirming the reliability of the measurement procedure and outcome variables.

The strong correlation between the PULMI and the MACS (Spearman's $\rho=-.78$, $p<.0001$) provides further evidence of its validity. However, the PULMI offers a more quantitative and precise measure of upper limb function. Although the MACS is an established classification system, it is not sensitive to post-intervention changes, whereas the PULMI is based on three-dimensional kinematics, which are routinely used to evaluate gait treatment outcomes (Gage and Novacheck 2001). In addition, functional differences between MACS levels are

unequal and children with CP are not equally distributed across the five levels; in contrast, the PULMI is scaled such that every 10 points below a score of 100 represents one standard deviation from the TD mean.

The PULMI analysis allows for the visualization and interpretation of RMS differences in upper limb kinematics (Figure 3a,b), providing useful insight into which variables contribute to an elevated score. For example, Figure 3a suggests that wrist flexion-extension motion affects the quality of upper limb motion for CP Participant 3, while Figure 3b demonstrates that elbow flexion-extension and pronation/supination deviations primarily affect upper limb function in CP Participant 20.

The PULMI resembles the Arm Posture Score (Riad et al. 2011) and the Arm Profile Score (Jaspers et al. 2011), in that all three indexes use an RMS difference between kinematic data of a child with CP and the average from a group of TD children to quantify upper limb movement pathology. The PULMI differs from these other measures in three important ways. First, the PULMI assesses upper limb motion during a single functional upper limb task, unlike the Arm Posture Score, which measures the deviation in arm posture during gait of children with hemiplegic CP, and the Arm Profile Score, which measures the deviation in upper limb motion during eight different upper limb tasks in children with hemiplegic CP. Second, the PULMI has been investigated in a wide range of CP subtypes, not only spastic hemiplegia. Third, the PULMI has been scaled for improved interpretability, such that every 10 points below 100 represents one standard deviation away from the TD mean.

As expected, PULMI scores were lower among children with CP compared to controls, indicating significant deviations in upper limb motion. Children with CP also demonstrated differences in temporal-spatial parameters, including a prolonged MT, due to prolonged grasp and release times (Butler et al. 2010b), and an increased IC *reach* and NMU, indicating less efficient and less smooth movements.

Among TD participants, peak velocities were greater during the first transport phase than *reach*, resulting in an increased ratio of $T_{1:reach}$ peak velocities (Table 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 et al. 1998). In general, the children with CP did not demonstrate this pattern, suggesting a more limited ability to modulate hand velocity.

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

Children with dyskinetic CP had significantly lower PULMI scores than children with spastic CP, indicating greater deviations in upper limb motions during the Reach & Grasp Cycle. Group differences may be attributed to the higher MACS levels in children with dyskinetic CP, as the small number of participants with dyskinesia available for testing limited our ability to control for level of upper limb function. However, our sample may be representative of upper limb function for children with dyskinetic CP, as Eliasson *et al.*

(2006) reported a higher MACS level (decreased upper limb function) for children with dyskinetic versus spastic CP.

Children with spastic CP commonly have elbow flexion spasticity and contractures (Manske 1990), which may contribute to reduced angular velocity of elbow extension during reaching, as seen for participants 1,3,13,15,19,21–23 (Table 1). Participants with dyskinetic CP also demonstrated a reduced angular velocity of elbow extension, perhaps due to difficulties performing sequential movements (Currá et al. 2000).

Children with dyskinetic CP demonstrate involuntary twisting, repetitive movements, and abnormal postures (Sanger et al. 2010), perhaps reflected during the Reach & Grasp Cycle by an increased NMU and IC *reach*. The NMU, higher in nearly all participants with CP regardless of movement disorder, was significantly higher in dyskinetic compared to spastic CP. In addition, children with more severe dyskinetic CP tended to reach in a more curved path than those with less severe dyskinesia (Table 1), similar to Gordon *et al.* (2006). The PULTSE, a logistic regression of 4 temporal-spatial parameters, correctly predicted 19 of 22 cases of spastic versus dyskinetic CP, indicating clear, quantitative differences between these two movement disorders.

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 et al. 2000). Indeed, the two children with ataxia demonstrated prolonged MT, an increased IC *reach*, and a greater NMU than any of the other children with spastic or dyskinetic CP.

In summary, the present study provides strong evidence that the PULMI profile, the PULTSE, and key temporal-spatial parameters of the Reach & Grasp Cycle precisely quantify and help delineate neuromotor abnormalities in spastic, dyskinetic, and ataxic CP. These measures have been shown to be valid and reliable, and thus have both research and clinical applications.

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Figure 1.

The shaded area represents the overall difference between a participant's data (solid line) and the mean from the reference dataset (dashed line) for elbow flexion extension. The root-mean-square (RMS) difference is calculated between the solid and dashed lines throughout the Reach & Grasp Cycle for elbow flexion-extension, as well as the other seven upper limb kinematic variables, to derive the raw PULMI score.

Figure 2.

(a) Histogram of PULMI scores for all typically developing children (n=30). The mean average RMS value ($PULMI_{raw}$) for the TD group was 9.18 ± 1.94 , median=9.20, and (b) Histogram of PULMI scores for children with spastic CP (n=13) and dyskinetic CP (n=9),

Figure 3.

Root-mean-square (RMS) difference values for all eight upper limb kinematic variables over the Reach & Grasp Cycle and the average RMS difference for all upper limb kinematic variables (raw Pediatric Upper Limb Motion Index) for (a) CP Participant 3 and (b) CP Participant 20.

SE = shoulder elevation, *SR* = shoulder rotation, *EF* = elbow flexion-extension, *Pro* = pronation-supination, *WF* = wrist flexion-extension, *WD* = wrist deviation, *TL* = trunk lean (flexion-extension), *TR* = trunk rotation.

Figure 4. 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).

Table 1

Participant demographics, PULMI scores, and key temporal-spatial measures during the Reach & Grasp Cycle.

Typically Developing Children (n=30)										
		Age (years)	Sex	PULMI	MT (sec)	IC Reach	NMU	Elbow Ext Reach (*sec)	Velocity T/ Reach	
Mean		10.9	14M 16F	100	5.05	116	4.8	47.8	1.62	
SD		4.1	F	10	1.07	13	1.1	23.4	0.53	
Children with Cerebral Palsy and Upper Limb Involvement (n=25)										
#	Primary Diagnosis	MA CS Level	Age (years)	Sex	PULMI	MT (sec)	IC Reach	NMU	Elbow Ext Reach (*sec)	Velocity T/ Reach
24	L hemiplegia	I	7.8	M	95.39	5.93	108.11	4.0	38.9	0.97
17	R hemiplegia	I	14.3	F	94.60	5.22	112.48	4.5	39.1	1.58
23	R hemiplegia	I	15.4	M	91.39	5.82	127.27	4.0	21.7	1.47
19	L triplegia	I	14.8	M	90.35	3.25	104.30	4.0	19.0	1.88
18	Quadriplegia, L n.d.	I	12.0	M	86.51	5.87	109.85	5.5	31.0	1.58
14	L hemiplegia	I	7.2	M	86.08	5.03	118.79	6.5	69.6	0.88
21	Quadriplegia, L n.d.	II	13.5	M	98.97	6.37	125.52	4.5	22.6	0.91
22	L hemiplegia	II	17.7	F	92.84	7.46	138.94	6.0	17.0	1.86
13	L triplegia	II	10.4	M	91.87	5.63	123.87	6.5	5.8	1.38

2	R hemiplegia	Spastic	II	5.8	M	80.28	6.0	130.	4.5	44.6	1.36
5							9	14			
1	R hemiplegia	Spastic	II	17.3	F	79.81	10.	166.	13.	9.6	0.80
5							68	82	5		
3	L hemiplegia	Spastic	II	15.3	F	74.56	12.	134.	5.0	7.0	0.83
							58	46			
1	L hemiplegia	Spastic	III	14.6	F	-0.54	10.	153.	10.	7.2	0.89
							55	88	5		
2	L hemiplegia	Dyskinetic	I	14.0	F	96.17	5.6	114.	4.5	29.9	1.32
							0	27			
1	L hemiplegia	Dyskinetic	I	14.1	F	76.17	5.0	116.	5.5	13.0	2.26
2							3	15			
1	L hemiplegia	Dyskinetic	II	5.8	F	71.90	7.5	133.	10.	17.1	1.33
1							5	30	0		
2	R hemiplegia	Dyskinetic	II	12.8	F	59.88	4.7	122.	6.5	17.2	1.32
7							7	37			
4	R hemiplegia	Dyskinetic	II	16.3	F	53.40	8.2	149.	9.5	2.9	0.90
							5	93			
7	R hemiplegia	Dyskinetic	III	7.1	F	64.71	10.	143.	10.	15.3	1.69
							38	75	0		
1	Quadriplegia, R n.d.	Dyskinetic	III	17.1	M	61.37	12.	202.	10.	8.6	0.97
							59	84	5		
2	R hemiplegia	Dyskinetic	III	10.0	F	30.91	6.7	185.	9.5	22.6	0.44
							2	14			
9	R hemiplegia	Dyskinetic	III	13.1	F	4.91	17.	160.	21.	19.1	0.54
							55	22	0		
1	L triplegia	Mixed (spastic & dyskinetic)	III	11.3	F	30.67	6.2	174.	7.5	2.4	0.50
6							2	82			
2	Quadriplegia, L n.d.	Mixed (ataxic & dyskinetic)	III	12.6	F	49.42	17.	309.	35.	11.7	2.68
6							89	33	0		
6	Quadriplegia, R n.d.	Mixed (ataxic & dyskinetic)	IV	7.0	F	20.00	18.	1197	95.	105.	0.96
							63	.00	0	9	
			Mean	12.3	9		8.4	186.	12.		
			n		M	67.26	7	54	1	24.0	1.25
			SD	3.7	16		4.3	214.	18.		
					f	29.54	4	78	5	22.9	0.55

PULMI = Pediatric Upper Limb Motion Index, MT = total movement time to complete the Reach & Grasp Cycle, IC Reach = index of curvature during the reach phase, NMU = number of movement units, Elbow Ext Reach = angular velocity of elbow extension during the reach phase, Velo T1 / Reach = ratio of the peak velocities of the wrist during the first transport phase (T1) and reach phase, MACS = Manual Ability Classification Scale, R/L = Right or Left, n.d. = non-dominant hand, M/F = Male or Female.

Table 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 children with cerebral palsy (CP, n=24).

	TD (n=12)		CP (n=24)	
	Spearman's rho	p-Value	Spearman's rho	p-Value
PULMI Score	.91	<.0001	.96	<.0001
MT	.89	.0001	.89	<.0001
IC <i>Reach</i>	.80	.0016	.84	<.0001
NMU	.47	.1240	.84	<.0001
Elbow Ext <i>Reach</i>	.88	.0002	.80	<.0001
Velo T_1 / <i>Reach</i>	.69	.0126	.70	.0001

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.

Typically Developing Children (n=30)				
	<i>IC Reach</i>	NMU	<i>Elbow Ext Reach</i>	<i>Velo T₁ / Reach</i>
Movement Time	0.04	0.18	-0.15	0.32
<i>IC Reach</i>	1.00	0.61	-0.17	0.13
NMU		1.00	-0.12	0.02
<i>Elbow Ext Reach</i>			1.00	-0.40
Children with Cerebral Palsy and Upper Limb Involvement (n=22)				
	<i>IC Reach</i>	NMU	<i>Elbow Ext Reach</i>	<i>Velo T₁ / Reach</i>
Movement Time	0.42	0.75	-0.37	-0.47
<i>IC Reach</i>	1.00	0.47	-0.40	-0.49
NMU		1.00	-0.31	-0.42
<i>Elbow Ext Reach</i>			1.00	-0.04