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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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A B S T R A C T

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 about 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 $=10.9\pm4.1$ years) and 25 children with CP and upper limb involvement (age $=12.3\pm3.7$ 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$_1$: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.

1. 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

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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., 2011a; Mackey et al., 2005, 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., 2011b; 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.

2. Methods

2.1. 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

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 (s)**	**IC reach**	**NMU**	**Elbow Ext (°/s)**	**Vel T_1/reach**
			Mean	**10.9**	**14M**	**100**	**5.05**	**116**	**4.8**	**47.8**	**1.62**
			SD	**4.1**	**16F**	**10**	**1.07**	**13**	**1.1**	**23.4**	**0.53**
Children with cerebral palsy and upper limb involvement (n=25)											
#	**Primary diagnosis**	**Movement disorder**	**MACS level**	**Age (years)**	**Sex**	**PULMI**	**MT (s)**	**IC reach**	**NMU**	**Elbow Ext reach (°/s)**	**Vel T_1/reach**
24	L hemiplegia	Spastic	I	7.8	M	95.39	5.93	108	4.0	38.9	0.97
17	R hemiplegia	Spastic	I	14.3	F	94.60	5.22	112	4.5	39.1	1.58
23	R hemiplegia	Spastic	I	15.4	M	91.39	5.82	127	4.0	21.7	1.47
19	L triplegia	Spastic	I	14.8	M	90.35	3.25	104	4.0	19.0	1.88
18	Quadriplegia, L n.d.	Spastic	I	12.0	M	86.51	5.87	110	5.5	31.0	1.58
14	L hemiplegia	Spastic	I	7.2	M	86.08	5.03	119	6.5	69.6	0.88
21	Quadriplegia, L n.d.	Spastic	II	13.5	M	98.97	6.37	126	4.5	22.6	0.91
22	L hemiplegia	Spastic	II	17.7	F	92.84	7.46	139	6.0	17.0	1.86
13	L triplegia	Spastic	II	10.4	M	91.87	5.63	124	6.5	5.8	1.38
25	R hemiplegia	Spastic	II	5.8	M	80.28	6.09	130	4.5	44.6	1.36
15	R hemiplegia	Spastic	II	17.3	F	79.81	10.68	167	13.5	9.6	0.80
3	L hemiplegia	Spastic	II	15.3	F	74.56	12.58	134	5.0	7.0	0.83
1	L hemiplegia	Spastic	III	14.6	F	-0.54	10.55	154	10.5	7.2	0.89
2	L hemiplegia	Dyskinetic	I	14.0	F	96.17	5.60	114	4.5	29.9	1.32
12	L hemiplegia	Dyskinetic	I	14.1	F	76.17	5.03	116	5.5	13.0	2.26
11	L hemiplegia	Dyskinetic	II	5.8	F	71.90	7.55	133	10.0	17.1	1.33
27	R hemiplegia	Dyskinetic	II	12.8	F	59.88	4.77	122	6.5	17.2	1.32
4	R hemiplegia	Dyskinetic	II	16.3	F	53.40	8.25	150	9.5	2.9	0.90
7	R hemiplegia	Dyskinetic	III	7.1	F	64.71	10.38	144	10.0	15.3	1.69
10	Quadriplegia, R n.d.	Dyskinetic	III	17.1	M	61.37	12.59	203	10.5	8.6	0.97
20	R hemiplegia	Dyskinetic	III	10.0	F	30.91	6.72	185	9.5	22.6	0.44
9	R hemiplegia	Dyskinetic	III	13.1	F	4.91	17.55	160	21.0	19.1	0.54
16	L triplegia	Mixed (spastic & dyskinetic)	III	11.3	F	30.67	6.22	175	7.5	2.4	0.50
26	Quadriplegia, L n.d.	Mixed (ataxic & dyskinetic	III	12.6	F	49.42	17.89	309	35.0	11.7	2.68
6	Quadriplegia, R n.d.	Mixed (ataxic & dyskinetic)	IV	7.0	F	20.00	18.63	1197	95.0	105.9	0.96
			Mean	**12.3**	**9M**	**67.26**	**8.47**	**186**	**12.1**	**24.0**	**1.25**
			SD	**3.7**	**16F**	**29.54**	**4.34**	**215**	**18.5**	**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, Vel T_1/reach = ratio of the peak velocities of the wrist during the first transport phase (T_1) and reach phase, MACS = Manual Ability Classification Scale, R/L = Right or Left, n.d. = non-dominant hand, M/F = Male or Female.