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Loss of independent limb control in childhood hemiparesis is related to time of brain injury onset

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Abstract

Aim—This study investigated the presence of inter-limb activity at the elbow joint in individuals with childhood-onset hemiparesis, including spontaneous mirror movements during unilateral tasks and the ability to suppress them during bilateral tasks.

Method—Eighteen individuals with hemiparesis were divided into three categories of injury timing: before birth (PRE-natal), around the time of birth (PERI-natal), and after 6 months of age (POST-natal). Individuals with hemiparesis, as well as 12 typically developing peers, participated in unilateral and bilateral elbow flexion and extension tasks completed at maximal and submaximal effort while muscle activity was monitored and motor output was quantified by two multiple degrees-of-freedom load cells.

Results—Significantly higher levels of paretic elbow flexion were found only in the PRE- and PERI-natal groups during the flexion of the non-paretic limb, which was modulated by effort level in both unilateral and bilateral tasks.

Interpretation—The bilateral activation of elbow flexors in the PRE-/PERI-natal groups indicates potential use of a common cortical command source to drive both upper extremities, while the POST-natal/typically developing groups' flexors appear to receive input from different supraspinal structures.

Keywords

cerebral palsy; childhood hemiparesis; mirror movements; childhood hemiplegia; arm coordination

The majority of daily living tasks are bimanual activities involving different actions with each arm. Mirror movements, or simultaneous activation of the same muscles in right and left limbs, are considered to be part of typical development during the first decade of life. They have been demonstrated to persist in distal joints of the upper extremity in hemiparesis following early brain injury during relatively uncontrolled distal unilateral tasks (Nass 1985; Farmer et al. 1991; Lazarus 1992; Kuhtz-Buschbeck et al. 2000). However, the functional impact of these movements has not been investigated during a bilateral task or at more

proximal joints, so the ability to independently control both upper extremities remains unclear in childhood-onset hemiparesis (CH).

Non-invasive brain stimulation has shown that early in typical development, both ipsilateral and contralateral motor evoked potentials (MEPs) can be elicited with transcranial magnetic stimulation (TMS) (Eyre et al. 2001). There is rapid differential development and the likelihood of ipsilateral MEPs is markedly decreased after approximately 6 months of age in a typically developing child, and is hypothesized to be related to activity-dependent withdrawal of ipsilateral corticospinal (CS) connections (Martin et al. 2007). However, in children with early onset CH, ipsilateral CS connectivity may be maintained from the non-lesioned primary motor cortex to the paretic limb (Eyre et al. 2007). The presence of ipsilateral connections has been correlated with the presence of observed mirror movements (Vandermeeren et al. 2009), and is one potential hypothesis for their presence.

Given that CH can occur over a range of ages both before and after typical withdrawal of the CS projections, it represents an ideal model for studying the impact of the time of brain lesion onset on the loss of independent limb control, or the ability to dissociate motor activity between arms. It was hypothesized that participants with early injuries would have decreased independent limb control, evidenced by more mirror movements, due to a presumed common source of command from the contralesional (ipsilateral to the paretic arm) primary motor cortex. Conversely, those with later injuries were not expected to demonstrate the same obligatory coupling between arms, due to a hypothesized use of different supraspinal structures to control each of the limbs.

This study used two multiple-degrees-of-freedom load cells and electromyographic (EMG) recordings during both maximal and submaximal unilateral and bilateral tasks in the upper extremity to quantify the relationship between torque generation and muscle activation in both limbs. In this way, we were able to accurately elucidate not only spontaneous inter-limb activity, as has been done in previous studies, but also a participant's ability to overcome such activity in a task that requires use of both upper extremities. The elbow joint was chosen because it is an example of a joint that is likely to be influenced by both corticospinal and reticulospinal systems (Baker 2011), and could demonstrate differences in performance if the neural structures involved in control of the paretic limb depend on the time of brain injury in CH.

Methods

Participants

A total of 120 possible CH candidates for the study were identified through the Cerebral Palsy Research Registry (Hurley et al. 2011), local clinics, newspaper advertisements and parent support groups. To be included, participants must have been at least 6 years of age and sustained a brain injury in the developing nervous system that resulted in unilateral upper extremity motor impairment. Participants could not have significant concurrent medical conditions, botulinum toxin injections to the upper extremity within 6 months of testing, or medications known to alter central nervous system activity. They were all in mainstream education. Timing of injury was ascertained by medical record review, including imaging results when available. PRE-natal injury was defined prior to approximately 34 weeks post-conceptual age (Folkerth 2005), and included the following etiology of injury confirmed by imaging: intraventricular hemorrhage (n=5), internal capsule ischemic damage (n=1). PERI-natal was defined from the late third trimester of gestation until 2 months following birth, and included imaging evidence of middle cerebral artery infarct (n=3). POST-natal injury was defined between 6 months and 10 years of age, and included imaging evidence of: intracranial bleed (n=1), middle cerebral artery infarct (n=1),

and arteriovenous malformation (n=1). All individuals with imaging reports (n=12) indicated injury to areas where corticofugal tracts would typically descend. Many recruits were excluded due to not meeting criteria (n=22), declining participation (n=10), not returning messages (n=51), participation in other studies (n=18), and requesting to stop (n=1). A convenience sample of typically developing (TD) participants (n=12) with no history of neurological injury was recruited for comparison to the CH groups. Of the potential candidates, 18 participants with clearly defined CH injuries (8 PRE-natal, 5 PERI-natal, and 5 POST-natal) and 12 TD controls completed the study. All participants provided informed consent and/or assent prior to enrolling in the study, which was approved by the Institutional Review Board of Northwestern University.

Participant's motor function was classified using the Gross Motor Function Classification System (GMFCS) (Rosenbaum et al. 2008), the Manual Abilities Classification Scale (MACS) (Eliasson et al. 2006), the Quality of Upper Extremity Skills Test (QUEST) (DeMatteo et al. 1992), and the Fugl-Meyer Motor Assessment (FMA) (Fasoli et al. 2009). Spasticity was manually measured using the Tardieu scale at slow (comparable to 30/second) and fast (as quickly as the examiner could move the participant) speeds (Mackey et al. 2004). Parent-reported outcome measures of function were assessed using the ABILHAND-Kids (Arnould et al. 2004) instrument.

Protocol

Participants were seated in a Biodex experimental chair (Biodex, Shirley, NY) with chest and lap straps to reduce trunk movement. Each of the participant's arms was placed in a fiberglass cast distal to the elbow to encompass all fingers in a neutral position, as shown in Figure 1A. The paretic (or non-dominant, for typically developing participants) arm was rigidly coupled to a stationary 6 degrees-of-freedom load cell (JR3, Inc., Woodland, CA), and the non-paretic (or dominant for TD participants) arm was coupled to an isokinetic dynamometer (Biodex System 3) with an integrated 6 degrees-of-freedom load cell (JR3, Inc.) set to allow elbow flexion and extension movements. Forces and moments measured by the load cells were converted to torques at the elbow based on a free body analysis of the upper limb, and used to provide real-time visual feedback. EMG electrodes (Delsys, Boston, MA) were placed over the belly of biceps brachii (BIC) and the lateral head of triceps brachii (TRI) following skin preparation. Data was collected at 1000 Hz after signals were low-pass filtered with the cut-off frequency at 500 Hz (8-pole analog Butterworth filter; Model 9064, Frequency Devices, Haverhill, MA, USA) to prevent aliasing and amplified with gains set to maximize the available input range of the analog-digital converter.

Participants completed a series of tasks. First, to establish a baseline for subsequent trials and for normalization, isometric maximal voluntary torques (MVTs) were completed in random fashion for elbow flexion (EF) and extension (EE) bilaterally with the arm held at 90° of elbow flexion. During each task, participants were instructed to relax the opposite limb. Then, isokinetic efforts in the non-paretic arm were completed at 100%, 50%, and 25% of maximal torque production in EE and EF. This was done in a discrete fashion at 30°/second and a range of motion between 70° and 140° of elbow extension. During this time the participant was instructed to relax the paretic arm. These trials are referred to as unilateral isokinetic (uni-IK) tasks.

Participants then completed a series of bilateral tasks in a randomized order. In preparation, they were trained to perform 25% of their elbow flexion MVT reliably in the paretic arm, starting with online visual feedback and progressing to verbal feedback of performance only at the end of a trial. They were allowed a tolerance of plus or minus 10% of the target for the trial to be considered successful, and all participants demonstrated at least 2 successful trials without visual or verbal feedback before attempting bilateral tasks. After training,

participants maintained 25% EF MVT on the paretic side, while concurrently performing 100% 50%, and 25% EE and EF efforts on the non-paretic side with visual feedback to guide performance of the non-paretic efforts. This bilateral task was completed with both isokinetic and isometric (with the dynamometer locked at 90° of elbow flexion) non-paretic arm conditions at each of the effort levels, in randomized order. These tasks are referred to as bilateral isokinetic (bi-IK) and bilateral isometric (bi-IM) tasks, respectively. Torque trace examples illustrating the uni-IK and bi-IK tasks are shown in Figures 1B–1E.

Data analysis

Joint torque data were filtered using a 250-ms moving average filter for all trials. The MVT was identified from the first set of trials as the maximal torque achieved in an intended direction. Each trial of the uni-IK sets was visually inspected for performance quality. For acceptable trials, the non-paretic EE and EF phases of movement were selected using the tracing from the dynamometer as a guide. Average paretic limb elbow torques were calculated during the time periods selected, and a cross correlation for elbow torques on both arms was completed across the entire trial period. Similar inspection and selection techniques were utilized in the bi-IK and bi-IM trial types. For the isometric trials, steady state portions of EE and EF were identified on the non-paretic arm torque trace. Torque averages were normalized by dividing by the relevant MVT. In the uni-IK trial type, ideal performance (no mirror movements) would be a paretic elbow torque of 0% MVT; in the bi-IK and bi-IM trial types, ideal performance would be 25% MVT.

EMG signals were visually inspected for artifacts, and contaminated trials were removed from analysis. Signals were rectified, low pass filtered using a Butterworth filter, and normalized to the maximum voltage across all trials. Data from biceps brachii (BIC) and triceps brachii (TRI) were cross-correlated between limbs over the entire trial period, and averaged over the selected EE and EF phases of non-paretic limb efforts.

Statistics

One-way analyses of variance (ANOVAs) were used to determine if there were differences in mean age of the four groups, and clinical examination scores of the three CH timing groups. For the computed measures, mixed model ANOVAs were used to analyze the dependent variables listed in Table 2. Independent variable factors that were considered in this model included group (PRE, PERI, POST, TD), and effort level (100%, 50%, 25% of MVT). The Least Significant Difference (LSD) post-hoc tests were used to determine differences between levels. Statistical analysis was completed using SPSS (version 19, SPSS, Inc.). A p-value of 0.05 was considered statistically significant for all tests.

Results

Table 1 summarizes characteristics of participants in this study. One-way ANOVAs did not reveal differences in the following clinical measures: GMFCS ($F=1.100$, $p=0.358$); MACS ($F=0.471$, $p=0.633$); FMA ($F=1.011$, $p=0.387$); QUEST-DM ($F=2.578$, $p=0.109$); QUEST-G ($F=2.357$, $p=0.130$); ABILHAND ($F=0.564$, $p=0.581$), Tardieu score for triceps at fast speeds ($F=0.085$, $p=0.919$). There was a significant difference found in the age of groups ($F=3.091$, $p=0.044$), where the POST-natal group was older than the PRE-natal and TD cohorts, and Tardieu score for biceps at fast speeds ($F=5.362$, $p=0.018$), where the POST-natal group had highest levels of spasticity. The Tardieu score at the slow speed was 0 for all participants in both biceps and triceps.

A complete list of main and interaction effects with post-hoc differences for calculated dependent variables is found in Table 2, and is highlighted in the following text.

Mirror activity in the paretic arm during unilateral non-paretic (uni-IK) tasks

During the non-paretic EE phase, there were main effects of group and effort with 100% MVT showing the greatest paretic limb torque. The PRE-natal group tended to generate a slight elbow flexion (EF) torque (0.6% MVT at 100% effort), whereas the PERI-natal, POST-natal, and TD groups tended to generate elbow extension (EE) torques (10.6%, 13.2%, 10.5% MVT at 100% effort, respectively). This was accompanied by a non-significant average paretic TRI activation of less than 15% of maximal EMG across all groups and effort levels.

In contrast, there were stark differences between groups during the isokinetic EF phase of movement in the non-paretic arm, where all groups produced elbow flexion torque in the paretic arm. There was a significant effect of group, effort, and group-by-effort interaction, with mirror activation levels as high as 50% of EF MVT in the paretic limb of the PRE-natal group, as shown in Figure 2. Significant post-hoc results showed PRE-/PERI-natal groups to be significantly different from the POST-natal/TD groups. There was also a significant effect of group and effort on average paretic BIC activation level, with approximately 30% of maximal EMG activation during the highest effort task in the PRE-natal group.

There was a significant effect of both group and effort on the correlation between the paretic and non-paretic BIC activation throughout the entire trial, with the PRE-/PERI-natal groups significantly different than the POST-natal/TD groups. In summary for a unilateral task, the isokinetic EF phase of movement in the non-paretic arm resulted in the highest levels of significant activity in the paretic arm, especially in the PRE- and PERI- natal groups.

Mirror activity in the paretic limb during bilateral (bi-IK and bi-IM) tasks

With the addition of a paretic limb EF requirement, nearly all of the significant effects were eliminated during the non-paretic EE phase in both isokinetic and isometric conditions.

For the non-paretic EF phase, several interesting significant effects were found. Average EF torque in the paretic arm of early injury groups is nearly unchanged from the unilateral tasks, as can be observed in Figure 2. Significant effects of group, effort and group-by-effort interaction were found in the average paretic elbow torque for both bilateral task types. As in the unilateral task, the PRE-natal group demonstrated especially high levels of EF torque in the paretic arm. There was also a main effect of effort in the average paretic BIC activation across groups.

In summary, the paretic limb of especially the PRE-natal group is driven most significantly during elbow flexion of the non-paretic elbow, even when the bilateral task required suppression of that activity to a lower level.

Discussion

This study found high levels of paretic elbow flexion activation when the non-paretic arm was flexing in the PRE- and PERI- natal groups, but not in the POST-natal or TD groups. The disparate nature of the responses suggests that the time of injury affects expression of inter-limb discoordination in CH.

Mirror movements have been shown to exist in typical development and thought to derive from concurrent activation of bilateral cortices (Mayston et al. 1999), but decrease significantly in the first decade of life (Gallea et al. 2011). This study cohort was tested at an age at which mirror movements are generally suppressed, so the presence of mirror movements should be considered atypical (Koerte et al. 2010). Unlike the CH groups, the TD group reliably demonstrated minimal activity in the non-dominant arm during unilateral

tasks completed with the dominant arm, which is consistent with previous findings at more distal joints of the upper extremity (Farmer et al. 1991; Kuhtz-Buschbeck et al. 2000). Although therapeutic interventions with the CH groups earlier in life may have contributed to partial improvements in mirror movements, there is convincing evidence for sustained mirrored activity in some of the CH groups. Concurrent activation of both cortices, hypothesized to be responsible for mirror movements early in typical development, are less likely to be responsible for persistence of mirror movements in the CH groups given a reduced number of corticofugal fibers from the lesioned hemisphere. Therefore other neural mechanisms should be considered to explain behaviors seen in the CH groups of the present study. We postulate that losses in corticofugal motor projections to the brainstem and spinal cord appears to engage contralesional backup systems that differ dependent upon the time of injury. In earlier injuries, preservation of ipsilateral projections may result in a shift of control of both limbs to the same cortical regions of the non-lesioned hemisphere, and can explain the strong mirror activity observed in this study.

Inter-limb activity in late hemiparetic group

Although mirror movements have been demonstrated in adults following stroke (Brunnstrom 1970; Bhakta et al. 2001), evidence for abnormal inter-limb activity at the elbow joint in our POST-natal cohort was less striking. Even at 100% of maximal elbow extension or flexion efforts on the non-paretic side during a unilateral task, the POST-natal group does not demonstrate significant paretic elbow torques. This is consistent with a previous study which found similar results in the first dorsal interosseus muscle in children with injuries after 4 months of age (Carr 1996). The present study did find a main effect of effort on paretic BIC activation during the EF phase of both unilateral and bilateral tasks. Although smaller muscle bulk in pediatric participants with hemiplegia may lead to some crosstalk, these results indicate that there is an increase in muscle activity even in the POST-natal group. However, BIC contributes only a percentage of elbow flexion torque, and the functional impact of the small increases in paretic BIC activation during maximal non-paretic efforts did not appreciably change the torque output of the paretic arm while it was supported in a static posture. Spasticity is unlikely to play a role during these experiments since the paretic arm was kept in the same posture in all experimental conditions. The higher Tardieu scores obtained at fast stretching speeds in the paretic limb, in combination with the timing of the injury after a period of direct ipsilateral corticospinal projections availability, may point to an upregulation of reticulospinal (RS) pathways. Hyperactive stretch reflexes may be due to an increased reliance on metabotropic monoaminergic inputs from the dorsal reticulospinal system resulting in an increase in motoneuron excitability altering the recruitment threshold of motoneurons (Fedirchuk and Dai 2004; Heckmann et al. 2005). This model of reorganization is hypothesized to occur following the loss of corticobulbar pathways due to a stroke in adulthood (Dewald et al. 1995; Ellis et al. 2007; Sukal et al. 2007), where indirect corticoreticular-reticulospinal connections from secondary motor cortices (Schwerin et al. 2008; Yao and Dewald 2010) are thought to be involved in control of the paretic limb. The measured increase in BIC activity in the POST-natal injury group of the current study could similarly be explained by contributions of the ipsilateral RS system, which has been shown to facilitate flexors (Davidson and Buford 2006), and may play a role during greater efforts (Baker 2011).

Inter-limb activity in early hemiparetic groups

In contrast to the POST-natal group, the PRE- and PERI-natal groups showed high average levels of mirrored elbow torque in the paretic arm during non-paretic elbow flexion (EF). There was previous evidence to indicate measurable changes in mirrored EMG activation during volitional tasks in early CH (Farmer et al. 1991; Carr 1996), but the current study is the first to show inter-limb activity in the upper extremity more proximally than the hand.

The magnitude of EF torque observed, in addition to high correlation coefficients of the paretic and non-paretic BIC muscles during unilateral tasks, suggests that a common neural source of EF command to both upper extremities may be responsible for task performance. Several studies have shown both contralateral and ipsilateral MEPs to be simultaneously elicited in children with PRE- and PERI-natal brain injuries (Carr 1996; Staudt et al. 2002; Eyre et al. 2007), demonstrating the possibility for abnormal retention of bilateral connectivity from one area of the cortex to both upper extremities in these two injury timing groups possibly due to retained ipsilateral projections (Eyre et al. 2001; Eyre et al. 2007) or abnormally branched pathways (Carr 1996). We are aware that although evidence points towards preservation of ipsilateral direct CS projections in the early CH groups, we cannot exclude the use contralateral CS projections. Depending on the extent of injury-related loss of corticofugal projections, the balance of ipsilateral and contralateral influence on the paretic arm could be altered. Future research combining diffusion tensor imaging (DTI), transcranial magnetic stimulation (TMS) and quantitative estimates of mirror movement, of the type presented in this paper, will allow for a richer understanding of this relationship. Despite potential variability in amount of ipsilateral contribution in the two early injury groups, this study demonstrated that in general the spontaneously high levels of elbow flexion torque produced during unilateral tasks could not be suppressed during bilateral tasks. This represents quantitative evidence for a loss of independent limb control, as well as a likely source of functional deficit. We observed differences in the correlation between biceps muscle activity during the isometric versus the isokinetic tasks. This may be related to differences in sensory feedback from the non-paretic elbow between the two motor tasks.

This study does have limitations. Firstly, a single joint task was chosen to ensure participant comprehension, but the expansion to multi-joint movements with careful instrumentation and experimental design may be necessary in future studies to examine the effects of losses of selective motor control during more complex motor tasks. Secondly, we verified the timing of injury for all participants but did not repeat the studies of previous investigators (Staudt et al. 2002; Eyre et al. 2007) to test for ipsilateral MEPs to the paretic limb in the PRE- and PERI-natal groups. Etiology of injury occurring uniquely in only one of the timing groups (for example, periventricular leukomalacia) has the possibility to confound the causal associations between injury timing, etiology, and motor outcomes. To fully dissect the inter-relationship between those variables, a study with many more participants would be required.

Clinical implications

The significant lack of independent limb control found in PRE- and PERI-natal groups in this study points to a likely source of disability in activities of daily living, and should not be overlooked in therapeutic interventions. Although cortical projections may not be identical between participants in early CH groups, the lack of independent limb control found suggests that the early injury groups would be more likely to benefit from bilateral practice in dissociating activity between upper limbs. Neural and behavioral efficacy has shown in cat models (Martin et al. 2007), and human therapies with an increased focus on bimanual performance have been developed (Gordon et al. 2007) and studied (Sakzewski et al. 2011). Clinical trials of bimanual therapy have not addressed the time of brain injury, a variable that is likely to affect outcomes based on information presented in the current study. Given the new evidence presented in this study, it can be concluded that individuals in the POST-natal group are likely to require targeted training to address the deficits other than mirror movements, for example the ability to selectively activate muscles within the paretic limb. In contrast, the early injury groups may uniquely benefit from a bimanual intervention given the magnitude of and inability to suppress mirror movements shown in this study.

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Figure 1.

Experimental setup and example trials. A.) Overhead view of the setup. Here, the left arm is weaker side (P, or ND) and the right arm is the stronger side (NP or D), with the right elbow centered over the axis of rotation of the isokinetic dynamometer. B.) Unilateral isokinetic trial for a typically developing participant. For example trials, the dashed line shows the non-dominant arm flexing at approximately 25% of MVT, and the solid line shows dominant arm elbow extension and flexion to approximately 50% of MVT. The light gray line represents positional movement of the isokinetic dynamometer, where the positive slope indicates extension and negative slope indicates flexion for this particular trial (note: the dynamometer trace is not related to y-axis scale). C.) Bilateral isokinetic trial for a typically developing participant. D.) Unilateral isokinetic trial for a PRE-natal participant. E.) Bilateral isokinetic trial for a PRE-natal participant.

Figure 2.
Paretic arm elbow joint torque during elbow flexion of the non-paretic arm in unilateral (A) and bilateral (B and C) tasks.

Table 1

Participant characteristics

ID	Gender	Age (yrs)	P arm/ND arm	GMFCS	MACS	FMA	QUEST (DM/G)	Tardieu at fast speed (BIC/TRI)	AH
PRE1	M	10.56	L	I	III	19	50.00/55.56	0/1	29
PRE2	F	10.56	R	I	II	30	67.18/44.44	0/0	35
PRE3	M	11.12	L	I	II	44	74.43/96.30	0/1	30
PRE4	F	12.47	R	I	II	37	73.50/37.04	2/2	39
PRE5	M	10.41	R	II	II	49	84.37/59.26	2/2	28
PRE6	M	7.31	L	I	I	66	100.00/100.00	0/0	NT
PRE7	M	9.13	R	II	I	45	74.43/66.67	2/0	33
PRE8	M	12.40	L	II	III	35	70.31/51.85	2/2	24
PER11	F	12.42	R	I	II	42	73.44/44.44	0/2	30
PER12	F	8.71	R	I	II	42	78.12/66.67	0/1	25
PER13	F	30.91	R	III	I	54	78.13/59.26	1/1	29*
PER14	M	8.57	R	II	III	37	84.37/59.23	1/0	26
PER15	M	11.61	R	II	II	43	81.25/59.26	0/0	30
POST1	M	14.18	R	II	III	25	57.81/22.22	2/2	25
POST2	M	14.88	R	II	III	28	50.00/22.22	2/2	36
POST3	M	32.41	R	II	I	51	89.06/62.96	2/0	36*
POST4	M	14.64	R	I	III	37	50.00/55.56	2/1	38
POST5	M	18.66	R	II	II	27	59.37/40.74	2/0	27
TD1	M	10.98	L						
TD2	M	12.32	L						
TD3	F	9.10	L						
TD4	M	9.01	L						
TD5	F	15.64	L						
TD6	F	16.46	L						
TD7	M	7.18	L						
TD8	F	9.09	L						

ID	Gender	Age (yrs)	P arm/ND arm	GMFCS	MACS	FMA	QUEST (DM/G)	Tardieu at fast speed (BIC/TRI)	AH
TD9	F	12.71	L						
TD10	M	14.49	L						
TD11	M	15.15	R						
TD12	F	6.52	L						

ID = subject identifier; P = paretic; ND = non-dominant; GMFCS = Gross Motor Function Classification System; MACS = Manual Ability Classification Scale; FMA = Fugl-Meyer Assessment; QUEST = Quality of Upper Extremity Skills Test; DM = Dissociated Movements Section; G = Grasp Section; BIC = biceps Tardieu score; TRI = triceps Tardieu score; AH = ABILHAND Kids score,

* indicates that ABILHAND was used instead of ABILHAND-KIDS for age appropriateness.

Table 2

Mixed model ANOVA results

DV	Task	GROUP, main effect and post-hoc comparisons							EFFORT, main effect and post-hoc comparisons				GROUP x EFFORT
		p-value	PRE/PERI	PRE/POST	PRE/TD	PERI/POST	PERI/TD	POST/TD	p-value	100/50	100/25	50/25	
pET-npEXT	uni-IK	0.036	0.032	0.036	0.008	0.964	0.998	0.960	0.014	0.009	0.015	0.846	p-value
	bi-IK	0.057							0.240				0.786
	bi-IM	0.013	0.070	0.633	0.113	0.040	0.001	0.392	0.536				0.810
pTRI-npEXT	uni-IK	0.125							0.253				0.994
	bi-IK	0.198							0.916				0.812
	bi-IM	0.203							0.409				0.914
pET-npFLEX	uni-IK	<0.001	0.142	<0.001	<0.001	<0.001	<0.001	0.701	<0.001	0.019	<0.001	0.009	0.793
	bi-IK	<0.001	0.062	<0.001	<0.001	0.005	0.007	0.510	<0.001	<0.001	<0.001	0.168	<0.001
	bi-IM	<0.001	0.020	<0.001	<0.001	0.053	0.381	0.151	<0.001	0.002	<0.001	0.033	0.021
pBIC-npFLEX	uni-IK	0.238							0.008	0.010	0.004	0.67	0.992
	bi-IK	0.338							0.005	0.030	<0.001	0.115	0.858
	bi-IM	0.830							<0.001	0.002	<0.001	0.154	0.830
ET-ET corr	uni-IK	<0.001	0.313	0.063	<0.001	0.011	<0.001	0.049	0.372				0.509
	bi-IK	0.053							0.356				0.999
	bi-IM	0.124							0.292				0.743
BIC-BIC corr	uni-IK	<0.001	0.328	<0.001	<0.001	0.001	<0.001	0.792	0.006	0.067	0.002	0.161	0.913
	bi-IK	0.011	0.306	0.548	0.038	0.701	0.005	0.016	0.005	0.021	0.002	0.390	0.006
	bi-IM	0.038	0.223	0.487	0.129	0.634	0.010	0.042	0.341				0.525
TRI-TRI corr	uni-IK	0.777							0.461				0.830
	bi-IK	0.007	0.136	0.034	0.360	0.001	0.414	0.003	0.908				0.998
	bi-IM	0.206							0.495				0.495

DV = dependent variable; uni-IK = unilateral isokinetic task; bi-IK = bilateral isokinetic task; bi-IM = bilateral isometric task; pET-EXT = paretic (or non-dominant in the TD group) elbow torque during non-paretic (or dominant in the TD group) elbow extension; pTRI-EXT = average paretic triceps activity during non-paretic elbow extension; pET-FLEX = paretic elbow torque during flexion of the non-paretic arm; pBIC-FLEX = average paretic biceps activity during non-paretic elbow flexion; ET-ET corr = correlation between elbow torque over the entire trial (i.e., flexion and extension of the non-paretic arm); BIC-BIC corr = correlation between biceps activation over the entire trial; TRI-TRI corr = correlation between triceps activation over the entire trial.