



Published in final edited form as:

Muscle Nerve. 2009 June ; 39(6): 800–809. doi:10.1002/mus.21231.

Temporal Characteristics of Lower Extremity Moment Generation in Children with Cerebral Palsy

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Abstract

Lower extremity weakness has been documented in children with cerebral palsy (CP). However, the temporal characteristics of moment generation have not been characterized, and they may be important to function. This study tested ankle, knee, and hip flexion and extension moment generation capabilities in children with CP and in able-bodied children. Maximum voluntary isometric contractions (MVIC), the maximum rates of moment development and relaxation, and the time to produce and reduce the moments were quantified. Relationships between the temporal measures, Gross Motor Function Measure-66 (GMFM-66), and MVICs were also examined. Children with CP had significantly reduced MVICs, maximum development and relaxation rates, and increased times to produce and reduce moments. The maximum rates of moment development and relaxation at some joints were correlated with the GMFM-66 and MVICs. These results suggest that both the magnitude and temporal characteristics of moment generation need to be targeted during therapeutic interventions for children with CP.

Keywords

Cerebral Palsy; Joint Moment; Impairments; Lower Extremity; Weakness

Introduction

Maximum voluntary contractions, either isometric or isokinetic, are used to quantify force generating capacity, an important determinant of functional ability.^{7·8·13·16} The magnitude of force is critical, but force must also be generated in a timely manner in order to be useful for activities of daily living (ADLs).³ A number of populations with neurological impairments have decreased maximum voluntary contractions compared to able-bodied individuals.¹ For example, children with cerebral palsy (CP) have significant amounts of lower extremity weakness, i.e. decreased maximum voluntary contractions, compared to their able-bodied peers.^{6·9·28} Even though these strength deficits have been correlated with

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Material Presented Elsewhere: Portions of this material were presented at the Society for Neuroscience Annual Meeting in November 2007, San Diego, CA.

functional activities such as gait and posture,^{5·10·13·16} most ADLs are performed using well-timed submaximal forces.^{23·24} Hence, the decrease in strength may not solely explain the functional difficulties, and other aspects of joint moment generation, in particular the temporal characteristics, should also be examined.^{3·6·17}

The temporal characteristics of joint moment generation (i.e. the rates of force development) have been quantified in some populations with neurological impairments. Jayaraman et al.¹² demonstrated that persons with incomplete spinal cord injury (SCI) had significantly decreased instantaneous plantarflexion moment (i.e. the moment available at 200 ms). Functionally, this altered moment profile would lead to an insufficient amount of plantarflexion moment available at the appropriate time in the gait cycle to safely ambulate in the community. Impaired rates of joint moment generation have also been shown in the upper extremities for persons with Parkinson's disease,⁴ and acute and chronic stroke.^{3·17} Different methods exist for characterizing the rates of joint moment development including instantaneous moment per time measures (e.g. Nm/s¹²) or the time taken to achieve a percent of maximal moment (e.g. the time from 10% to 70% of the maximum voluntary contraction¹⁷). The former is generally averaged over a brief time period to achieve an average rate of moment development, while the latter eliminates the effect of amplitude differences. Both measures have provided insight into moment generation capabilities that is not captured by solely quantifying maximum voluntary contractions.

While lower extremity weakness has been established in children with CP, the temporal characteristics of joint moment generation have not been examined. Given that children with CP have alterations in their muscular architecture^{11·15·18} and their ability to voluntarily activate a muscle,^{20·25} it would be expected that children with CP would also demonstrate alterations in their joint moment profiles, including changes to the temporal characteristics. Therefore, the first objective of this study was to examine the temporal characteristics of joint moment generation in the lower extremities of children with CP compared with able-bodied children by calculating maximum joint moment development and relaxation rates, and the time taken to produce or reduce the maximum voluntary isometric contraction (MVIC). This was completed using isometric contractions for six lower extremity degrees-of-freedom (DOF), specifically hip, knee and ankle flexion/extension. Isometric contractions were used, because they have proven to be a reliable measurement in subjects with neurological impairments, have been correlated to functional activity,¹ and were easy to understand for the children participating. The second objective of this study was to examine the relationships between the temporal characteristics, MVICs, and the Gross Motor Function Measure – 66, a multi-component rating scale used to quantify motor capabilities of children with CP. We hypothesized that children with CP would not only have decreased MVICs as previously seen, but that they would also have altered temporal characteristics of moment generation, and that these measures would be correlated with function. Characterizing moment generation profiles in children with CP may provide insight into how alterations in moment generation capabilities may affect performance of functional activities such as posture and gait. Furthermore, this characterization may allow clinicians to develop more effective therapies to improve ADLs.

Materials and Methods

Subjects

Twenty able-bodied (AB) subjects without neurologic or orthopedic injury (12 males and 8 females, mean age 11.6 ± 1.7 years, mass 41.4 ± 9.5 kg) and six children with CP (4 males and 2 females, mean age 12.5 ± 2.7 years, mass 45.4 ± 17.6 kg) were recruited for this study. All children were between 8 to 15 years of age, were able to comply with instructions, and demonstrated understanding of the joint moment visual biofeedback through a questionnaire

and a series of videos specific to the task being performed. Additionally, children in the CP group were assessed to be at levels I-III on the Gross Motor Functional Classification System (GMFCS), and had not had surgery within the past year. The characteristics for the subjects with CP are summarized in Table 1. The experimental protocol was approved by the Institutional Review Board at Arizona State University. All parents/guardians of the children provided written informed consent, while each child provided written informed assent.

Experimental Setup

The experimental setup (Fig. 1) was designed for real-time monitoring and display of forces/torques for multiple DOF. A customized lower extremity footplate incorporating a six-axis force/torque sensor (MC36-1000, AMTI, Watertown, MA, USA) was integrated with a fully adjustable chair (Biodex System 3, Biodex Medical Systems, Inc., Shirley, New York, USA). The chair was placed in a semi-reclined position with the footplate positioned such that the subject's hip and knee were fixed at 75° and 45° flexion, respectively, while the ankle was at 10° plantarflexion. The angles for hip, knee, and ankle were chosen because they were approximately mid-range for range of motion for children with CP.¹⁶ Moreover, these values were similar to positions used successfully during maximum voluntary contraction testing by Wiley and Damiano²⁸ and were not likely to be difficult for any of the children with CP to achieve. For testing, the trunk and pelvis were stabilized using buckle straps, and the foot of the side being tested was strapped to the footplate. The contralateral leg sat on a separate footrest to eliminate its interference with the leg being tested. Finally, visual biofeedback (described below) was displayed on an eye-level computer monitor approximately 60 cm in front of the subjects.

Analog voltage signals from the force/torque sensor were sampled at 500 Hz from a data acquisition card (PCI-6031E, National Instruments Corporation, Austin, TX) using customized software developed in LabVIEW™ (National Instruments Corporation, Austin, TX). The measured forces and torques, anthropometric measures, and limb configuration (i.e. joint angles) were used in static equilibrium equations to calculate isometric net joint moments for the hip, knee, and ankle. Force/torque data and calculated joint moments were stored on a personal computer for post-processing.

The biofeedback paradigm, based on net joint moments, provided a display of the net joint moment at a single joint in the form of a filled arc. The angular extent and direction of the arc fluctuated to represent the instantaneous amplitude and direction of the net joint moment (Fig. 1 inset). The software presented real-time visual biofeedback at a rate of 50 Hz. This biofeedback paradigm was designed so that it could be easily interpreted by subjects.

Experimental Protocol

Subjects were seated in the apparatus as described above. Before starting, each subject verbally indicated that they understood both the task at hand and the visual biofeedback. Subjects were given several minutes to become comfortable with the tasks. For testing, subjects were instructed to push in a specific direction (e.g. ankle plantarflexion) as hard and quickly as possible, hold for two seconds, and relax as quickly as possible. Auditory cues for starting and stopping were provided by the software at 1 and 3 seconds, respectively and were synchronized with data collection. Data was collected for a total of 5 seconds. Five second trials were selected to minimize the subject's fatigue. During each trial, subjects were provided with the visual biofeedback described above, and verbal encouragement. Each subject completed 3 trials for each of the 6 DOF of interest in the following order: plantarflexion, dorsiflexion, knee flexion, knee extension, hip flexion, and hip extension.

Approximately 30 seconds of rest were given between trials. Both the right and left legs were tested.

Subjects with CP were also evaluated using the Gross Motor Function Measure – 66 (GMFM-66). The GMFM-66 is a reliable, functional measure developed for children with CP.^{22,27} It was administered by the same board-certified pediatric physical therapist for all subjects.

Data Analysis

The data collected were used to evaluate the subject's MVICs as well as the temporal characteristics of joint moment generation. To calculate MVICs, the raw data were filtered using a 250 ms moving window average, and the MVIC for each trial was calculated as the maximum value found during that trial. The largest value of the 3 trials was selected as each subject's MVIC. MVIC values for able-bodied children were related to body mass, therefore, MVICs were normalized to body mass for group comparisons.

Temporal characteristics of joint moment generation were examined using 5 measures: reaction time (RT), time of moment generation (T_{on}), time of moment reduction (T_{off}), the maximum rate of moment development (MD_{max}), and the maximum rate of moment relaxation (MR_{max}). For these calculations, raw data were smoothed using a 25 ms moving window average. Three segments were defined on the moment profile: the initial segment (auditory sound to 5% MVIC), the ascending segment (10-70% MVIC while generating the moment), and the descending segment (70-10% MVIC while relaxing). The ascending segment limits of 10% and 70% have previously been shown to give consistent values.¹⁷ RT was the time of the initial segment. T_{on} and T_{off} were the times of the ascending and descending segments, respectively. MD_{max} was the maximum slope calculated for a best fit line of a 100 ms moving window on the ascending segment. MR_{max} was defined similarly for the descending segment.

Trials in which the child did not follow directions (i.e. the child started before the auditory cue, pushed in the wrong direction, or failed to stop pushing at the end of the trial) were excluded from analysis. For both groups, this represented approximately 15% of all trials. All temporal measures were averaged across the 3 like-trials. RT was further averaged across all DOF. The values for all subjects were right-left averaged, since subjects with CP did not display right-left differences. An example data trace with the segments depicted is provided in Fig. 2.

Statistical Analysis

Group comparisons for age, body mass, and the calculated values for each DOF were analyzed statistically using independent samples t-tests, which were planned *a priori*. All dependent variables for both groups had normal distributions. For children with CP, relationships between the moment generation measures and the GMFM-66 were analyzed using Spearman's Rank Correlations. This conservative, non-parametric test was chosen because of the small sample of subjects with CP. All statistical analyses used SPSS 15.0 (SPSS Inc., Chicago, IL), and an alpha level ≤ 0.05 was used to determine significance. Data are presented as mean \pm standard error of the mean.

Results

Raw data traces of a plantarflexion joint moment for four subjects (CP4, CP5, AB6, and AB20) are shown in Fig. 3. These data traces are representative of differences between groups.

Subject Characteristics

There were no statistical differences in age or body mass ($p>0.05$) between the two groups.

Reaction Time

RT was not statistically different in children with CP compared to the able-bodied children (0.54 vs. 0.49 s, respectively).

Maximum Voluntary Contractions

Children with CP had decreased MVICs for all DOF except knee extension ($p<0.05$, Table 2).

MD_{max}

Children with CP had decreased MD_{max} for all DOF ($p<0.05$, Fig. 4a, Table 3).

MR_{max}

Children with CP had decreased MR_{max} for all DOF ($p<0.05$, Fig. 4b, Table 3).

T_{on}

Children with CP had increased T_{on} for all DOF ($p<0.05$, Fig. 5a, Table 4).

T_{off}

Children with CP had increased T_{off} for plantarflexion, dorsiflexion, knee flexion, and hip extension ($p<0.05$, Fig. 5b, Table 4).

Correlations

Spearman's rho values for all correlations are reported in Table 5. GMFM-66 scores were correlated with the MVICs for dorsiflexion and knee extension, as well as MR_{max} for plantarflexion and dorsiflexion. GMFM-66 scores were not correlated with MVICs or MR_{max} at other joints or with T_{on} , T_{off} , or MD_{max} at any joints. The MVICs at each joint were examined for correlations with the temporal measures at that specific joint. The MVIC was correlated with T_{on} for hip flexion; with MD_{max} for plantarflexion, knee extension, and hip flexion; and with MR_{max} for plantarflexion, dorsiflexion, knee extension, and knee flexion. MVICs were not correlated with T_{off} at any joint.

Discussion

We hypothesized that children with CP would not only have significant impairments in maximal isometric contractions (as shown by earlier research studies), but they would also demonstrate significant impairments in the temporal measures of moment generation at the hip, knee, and ankle. We tested this hypothesis by asking able-bodied children and children with CP to complete a series of isometric contractions by pushing as hard and quickly as possible and then relaxing as quickly as possible. Children with CP demonstrated differences in their moment generation profiles including: (1) decreased MVICs; (2) decreased maximum rates of moment development and relaxation; and (3) increased time needed to generate and reduce moments. Further, a few temporal measures were correlated to the GMFM-66 and MVICs.

Maximum Voluntary Isometric Contractions

As expected, children with CP showed decreases in MVICs at all three joints when compared to able-bodied children. It is important to note that the short trial length selected

(5 seconds) may not have been a sufficient amount of time to allow some subjects to reach their maximal values, and as such, the absolute values should be regarded with caution. However, despite this and the small number of children with CP, the MVICs expressed as percentages of able-bodied children were similar to values calculated by previous studies (Table 2). Additionally, like Wiley and Damiano,²⁸ the greatest deficits were plantarflexion, dorsiflexion, and hip extension (38, 44, and 53%, respectively). Unlike previous studies,^{7,13} the knee extension MVIC was not significantly different in children with CP when compared to able-bodied children. This was likely a result of the small sample size, as well as the high functional level of this group. However, the knee extension MVIC was correlated with the GMFM-66 score as reported by Damiano et al. (2000).⁷

Temporal Measures

In addition to significant strength decreases, children with CP also demonstrated significant changes in temporal aspects of their moment generation capabilities. Changes in the temporal characteristics of the moment generation profile could be related to both a change in the amount of moment generated over a given time period (i.e. ΔM) or to a change in time to generate a given amount of force (ΔT). We have shown that both aspects are altered in children with CP, thereby compounding the deficits in force generation. MD_{MAX} and MR_{max} provided information regarding the amount of force generated in a given time. The change in the ΔM of the slopes are apparent in the example data traces provided in Fig. 3, as well as the significant differences for MD_{max} and MR_{max} found at all joints. Like the MVICs, MD_{max} , expressed as percentages of able-bodied children, indicated that the largest deficits were in plantarflexion, dorsiflexion, and hip extension (22, 25, and 23%, respectively). When averaged across all 6 DOFs, children with CP had only 28% of MD_{max} and 32% MR_{max} when compared to able-bodied children. Furthermore, the change in the ΔT is apparent in the values of T_{on} and T_{off} which documented changes in time that were independent of the maximum joint moment. Regardless of how much joint moment was being generated, children with CP had significantly increased times compared to able-bodied children to generate and relax the available joint moment. When averaged across all 6 DOFs, it took children with CP 89% longer to generate the moment and 71% longer to reduce the moment. Thus, for ADLs, not only do children with CP have decreased joint moments available, but the rates of moment generation and relaxation are also greatly reduced. Although tested in an isometric environment, these deficits may have implications for the ability of children with CP to respond to and recover from dynamic perturbations that exist during ADLs. Functional implications are further suggested through the correlations between MD_{max} , MR_{max} , GMFM-66, and the MVICs.

Some aspects of the temporal data presented here are consistent with results reported in the literature. Lee et al.¹⁴ showed that with electrical stimulation children with CP had slower muscle contractile characteristics compared to able-bodied children. Furthermore, these findings in children with CP are consistent with studies on other neurologically impaired subjects. Temporal deficits have been shown in the upper extremities of patients with stroke,^{3,17} as well as the lower extremities in patients with incomplete SCI.¹² Jayaraman et al.¹² suggests that these temporal deficits might have great functional implications, especially in activities such as walking that require repetitive, reciprocal activations of the muscle. Like persons with incomplete SCI, children with CP may not be able to generate enough joint moment in the amount of time available to sufficiently generate forward propulsion.

Potential Mechanisms

The reduced strength of children with CP, which was exhibited in this study and in previous studies, could be due to impairments in neural activation and/or changes in muscle

properties. Data from several different studies in the literature suggest that it is combination of both neural and muscular factors^{11,18,20,25}.

The nervous system modulates muscle force by using both recruitment and rate modulation.¹⁹ Previous studies have suggested that both the number of motor units that can be voluntarily activated and the maximum firing rate may be altered in children with CP.^{20,25} Rose and McGill²⁰ examined neuromuscular activation (i.e. the ratio of surface electromyogram (EMG) amplitude to maximal M-wave amplitude) in children with CP. Surface EMGs for the gastrocnemius and tibialis anterior were measured during plantarflexion and dorsiflexion MVICs, and the amplitude of the M-wave was measured during electrical stimulation of either the peroneal or tibial nerve. During voluntary contractions, children with CP had lower surface EMGs than their able-bodied peers, but their M-wave amplitudes were comparable, thereby resulting in a lower neuromuscular activation ratio. From this, the authors concluded that children with CP had an equivalent number of motor units available; however, children with CP voluntarily activated fewer motor units during MVIC testing. Moreover, the relationship between motor unit recruitment and firing rates was similar between able-bodied children and children with CP for low level contractions (<20% MVIC), but the projected maximum firing rate of children with CP was approximately half that of able-bodied children. Therefore, children with CP may not be able to increase motor unit firing rates above a certain point, thereby limiting the force output of that muscle. In this study, although lower activation ratio and lower peak firing rate may explain the differences in MVICs, it is unlikely that they account for the observation that children with CP have lower rates of moment development and relaxation. Neural control mechanisms in children with CP may differ in a manner that reduces the rate of change in recruitment or reduces the rate of increase in firing rate, both of which would contribute to the observed differences in temporal measures.

Muscle properties of children with CP have also been shown to be different from their able-bodied peers.^{11,18} Rose et al.¹⁸ showed that children with CP have increased variation in the size of muscle fibers, as well as altered distribution of Type-I and Type-II fibers. The altered fiber type distribution was highly variable between subjects as 3/10 had a highly disproportionate count (>70%) of Type-I fibers, while another subject had a highly disproportionate count (>70%) of Type-II fibers. More recently, Friden and Lieber¹¹ showed that spastic muscle fibers from children with CP had shorter resting lengths, which would affect the force generating capability. Slow twitch muscle fibers have 25% of the maximum shortening velocity of fast twitch fibers². Although shortening velocity would influence rate of moment production, at most, this could account for the rates of children with CP being 25% of the rates of able-bodied children. For plantarflexion, dorsiflexion, and hip extension values of 22, 25, and 23%, respectively of the able-bodied rates were calculated. Since all of the muscles tested in this study probably contain a mixture of fiber types, the effect of fiber type distribution likely accounts for only a portion of the observed differences in rates of moment development and relaxation. While changes in muscular architecture may account for some of the changes to the temporal characteristics of moment generation in children with CP, this strongly suggests the involvement of a neural component as well.

Future Considerations

This study measured the temporal properties of joint moment generation during isometric tasks. Functional activities require dynamic force generation using both concentric and eccentric contractions. Although a few correlations were found between the temporal characteristics and the GMFM-66, isometric tasks may not accurately convey the moment generation deficit that is experienced during ADLs. Future studies should examine these temporal moment generation properties under concentric and eccentric isokinetic tasks.

Furthermore, it will be important to perform these measurements on a larger sample of children with CP that spans a broader range of neuromotor deficits than the group used in this study.

This study provides a characterization of lower extremity motor function that includes both strength and temporal measures that we believe may have clinical relevance. Exercise interventions in children with CP have resulted in increased strength.⁵ Therefore it is possible that properly designed therapeutic interventions could improve temporal characteristics of moment generation in a manner that improves functional ability during ADLs. It is suggested that both strength and the temporal aspects of moment generation should be monitored and trained in the clinic.

Acknowledgments

Funding for this work was provided by IGERT NSF (NSF-DGE-9987619) (A. Downing) and the National Institute of Neurological Disorders and Stroke: National Research Service Award (1 F31 NS053010) (A. Downing). The authors gratefully acknowledge Manoshi Bhowmik-Stoker, Alison Conovaloff, Elliott Downing, and Jaime Stovall for their help conducting this study, Dr. Meghan Warren for assistance with the statistical analysis, and the children who participated.

Abbreviations

ADLs	activities of daily living
CP	cerebral palsy
DF	dorsiflexion
DOF	degrees of freedom
EMG	electromyogram
GMFCS	Gross Motor Functional Classification System
GMFM-66	Gross Motor Function Measure – 66
HE	hip extension
HF	hip flexion
KE	knee extension
KF	knee flexion
MD_{max}	maximum rate of moment development
MR_{max}	maximum rate of moment relaxation
MVIC	maximum voluntary isometric contraction
PF	plantarflexion
ROM	range of motion
RT	reaction time, time from auditory signal to 5% MVIC
SCI	spinal cord injury
T_{on}	time from 10% to 70% MVIC on ascending segment
T_{off}	time from 10% to 70% MVIC on descending segment

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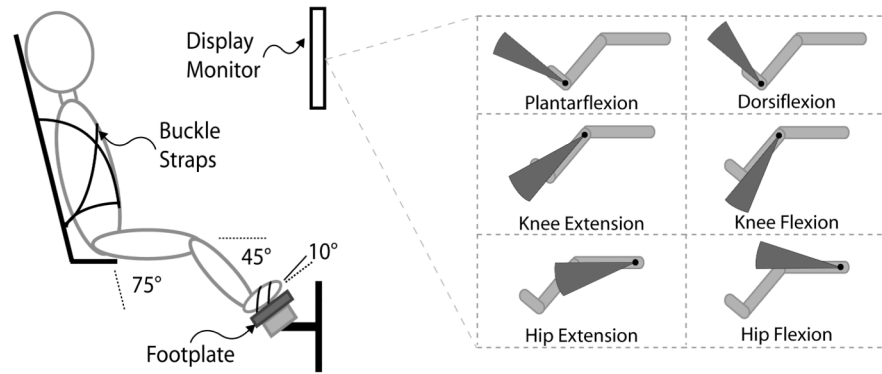


FIGURE 1. Experimental setup and visual biofeedback. The inset demonstrates the visual biofeedback used during testing. The angular extent of the arc varied in real-time to indicate the current value of the amplitude and direction of a specific joint moment.

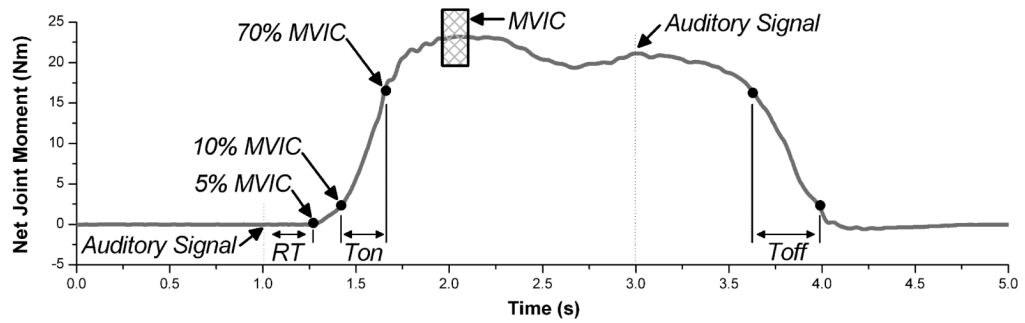


FIGURE 2.

Example joint moment profile. Raw data were filtered using a 25 ms moving window average. The following 3 segments were defined: initial segment (auditory sound to 5% MVIC), ascending segment (10% to 70% MVIC while generating force), and descending segment (70% to 10% MVIC while relaxing). Auditory signals, cueing the subject to start and stop pushing, were given at 1 and 3 seconds. The MVIC, calculated the maximum value of a 250 ms moving window average (applied to raw data), is indicated by the hatched rectangle. RT is the time from the auditory sound to 5% MVIC. T_{on} and T_{off} are the times taken for the ascending and descending segments, respectively.

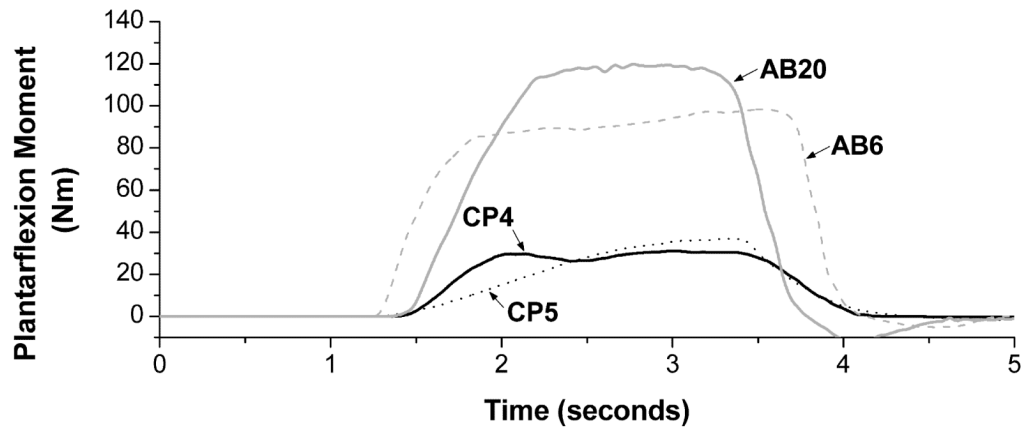


FIGURE 3.

Example data traces. Data has been filtered using a 25 ms moving window average. Two subjects with CP (CP4 and CP5) and two able-bodied subjects (AB6 and AB20) were chosen for plotting and are representative of differences seen between the groups. The two subjects with CP have decreased MVICs as well decreased rates of moment development and relaxation.

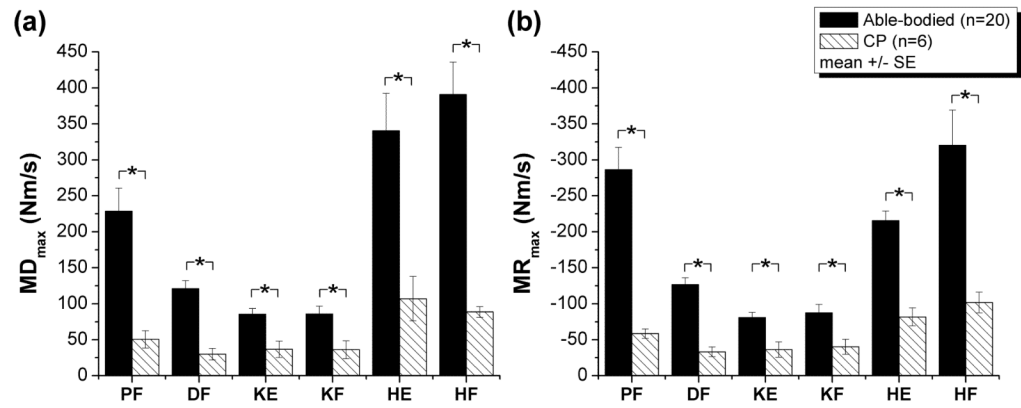


FIGURE 4.

MD_{max} (a) and MR_{max} (b) for the 6 DOFs in children with CP compared to able-bodied children. Children with CP had reduced maximum rates of moment development and relaxation for all DOF. * indicate significant differences ($p < 0.05$) between children with CP and able-bodied children. DOF abbreviations are defined in Table 2.

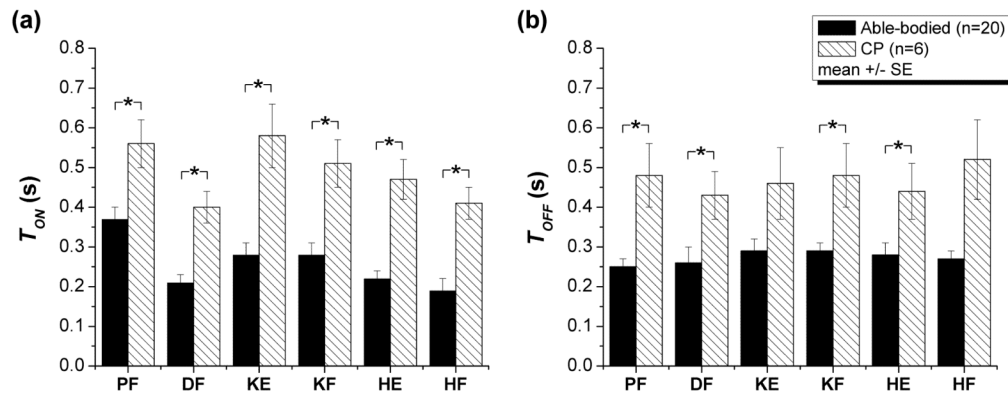


FIGURE 5.

T_{on} (a) and T_{off} (b) for children with CP compared to able-bodied children for the 6 DOFs tested. Children with CP needed increased time to produce a joint moment (all DOF) and increased time to reduce a joint moment (plantarflexion, dorsiflexion, knee flexion, and hip extension). * indicate significant differences ($p < 0.05$) between children with CP and able-bodied children. DOF abbreviations are defined in Table 2.

Table 1

Characteristics of children with cerebral palsy

Subject	Gender	Diagnosis	Age (Yr)	Mass (kg)	GMFCS	Surgeries
CP1	F	Spastic Diplegia	9.8	61.2	II	None
CP2	M	Spastic Hemiplegia	8.8	25.0	I	None
CP3	M	Spastic Diplegia	14.3	57.5	II	None
CP4	M	Spastic Diplegia	15.2	64.6	III	Heel cord lengthening (both), dorsal rhizotomy
CP5	F	Spastic Diplegia	14.7	34.3	II	Heel cord lengthening (both), foot derotation (L)
CP6	M	Quadraplegia, Mixed	12.3	29.7	I	Heel cord lengthening (both)
CP Average			12.5	45.4		
Able-Bodied Average			11.6	41.4		

GMFCS - Gross Motor Functional Classification Scale, I - Move without restriction. Limitations in advanced skills. II - Walk without assistive devices; limitations walking outdoors and in community. III - Walk with assistive devices; limitations walking outdoors and in community.

Table 2

Maximum voluntary contractions for the 6 DOF. The left hand portion of the table presents the normalized MVIC data from this study. The right hand portion presents MVIC data from previous studies on children with CP expressed as a percentage of maximum voluntary contractions recorded from able-bodied children in the that study. Children with CP had decreased MVICs for all DOF except knee extension.

DOF	NORMALIZED MVIC (Nm/kg)		p-value	Current Study	NORMALIZED MAXIMUM VOLUNTARY CONTRACTION (% OF VALUE FOR ABLE-BODIED CHILDREN)					
	Able-bodied Children (n=20)	Children w/ CP (n=6)			Ross & Engsborg ²¹	Danniano et al. ⁷	Wiley & Damiano ²⁸	Thelen et al. ²⁶	Rose & McGill ²⁰	
PF	2.18 ± 0.15	0.82 ± 0.20	0.000	38	-	-	39	-	48	
DF	-0.81 ± 0.04	-0.36 ± 0.10	0.000	44	-	-	41	-	26	
KE	-0.67 ± 0.06	-0.52 ± 0.18	0.281	78	63	63	63	43	-	
KF	0.71 ± 0.07	0.41 ± 0.13	0.045	58	38	38	68	51	-	
HE	2.51 ± 0.19	1.32 ± 0.21	0.003	53	-	-	44	59	-	
HF	-1.66 ± 0.06	-0.98 ± 0.18	0.013	59	-	-	57	76	-	

Data are mean ± standard error. MVICs are normalized to body mass (Nm/kg). Abbreviations are as follows: plantarflexion (PF), dorsiflexion (DF), knee extension (KE), hip flexion (HF), maximum voluntary isometric contraction (MVIC), and degrees-of-freedom (DOF).

p-values in **bold** indicate significant differences ($p < 0.05$) between able-bodied children and children with CP.

Table 3

MD_{max} and MR_{max} for the 6 DOF. Children had significantly decreased rates of moment development and relaxation for all 6 DOF.

DOF	MD_{max} (Nm/s)		MR_{max} (Nm/s)		p-value
	Able-bodied Children (n=20)	Children w/ CP (n=6)	Able-bodied Children (n=20)	Children w/ CP (n=6)	
PF	228.7 ± 32.1	50.7 ± 12.0	-286.3 ± 31.1	-58.4 ± 6.5	0.001
DF	121.1 ± 11.3	29.9 ± 8.1	-126.6 ± 9.7	-33.1 ± 6.8	0.000
KE	85.8 ± 11.2	36.2 ± 12.4	-87.4 ± 11.7	-40.3 ± 10.4	0.045
KF	85.6 ± 8.0	36.9 ± 11.5	-80.7 ± 7.3	-36.3 ± 10.6	0.006
HE	390.9 ± 44.9	88.7 ± 7.4	-320.3 ± 48.9	-101.8 ± 14.5	0.024
HF	340.4 ± 52.0	107.1 ± 31.0	-215.7 ± 13.3	-81.7 ± 12.6	0.000

Data are mean ± standard error. MD_{max} – maximum rate of moment development. MR_{max} – maximum rate of moment relaxation. Other abbreviations are defined in Table 2. p-values in **bold** indicate significant differences ($p < 0.05$) between able-bodied children and children with CP.

Table 4

T_{on} and T_{off} for the 6 DOF. Children showed increased time taken to produce the joint moment for all 6 DOF, as well as increased time taken to reduce the joint moment for plantarflexion, dorsiflexion, knee flexion, and hip extension.

DOF	T_{on} (s)			T_{off} (s)		
	Able-bodied Children (n=20)	Children w/ CP (n=6)	p-value	Able-bodied Children (n=20)	Children w/ CP (n=6)	p-value
PF	0.37 ± 0.03	0.56 ± 0.06	0.004	0.25 ± 0.02	0.48 ± 0.08	0.001
DF	0.21 ± 0.02	0.40 ± 0.04	0.000	0.26 ± 0.04	0.43 ± 0.06	0.037
KE	0.28 ± 0.03	0.51 ± 0.06	0.000	0.29 ± 0.02	0.48 ± 0.08	0.119
KF	0.28 ± 0.03	0.58 ± 0.08	0.001	0.29 ± 0.03	0.46 ± 0.09	0.004
HE	0.19 ± 0.03	0.41 ± 0.04	0.000	0.27 ± 0.02	0.52 ± 0.10	0.011
HF	0.22 ± 0.02	0.47 ± 0.05	0.000	0.28 ± 0.03	0.44 ± 0.07	0.054

Data are mean ± standard error. T_{on} – time from 10% to 70% on the ascending portion of the moment profile. T_{off} – time from 70% to 10% on the descending portion of the moment profile. Other abbreviations are defined in Table 2.

p-values in **bold** indicate significant differences ($p < 0.05$) between able-bodied children and children with CP.

Table 5

Spearman's rho reported for correlations between (a) Gross Motor Function Measure – 66 and (b) maximum voluntary isometric contractions (MVIC).

DOF	(a)				(b)				
	MVIC	MD_{max}	MR_{max}	T_{on}	T_{off}	MD_{max}	MR_{max}	T_{on}	T_{off}
PF	0.77	0.77	-0.94	0.60	-0.26	0.83	-0.83	0.54	0.03
DF	0.81	0.43	-0.94	0.49	-0.71	0.75	-0.93	0.35	-0.23
KE	0.89	0.61	-0.60	0.26	0.54	0.81	-0.83	-0.09	0.49
KF	0.66	0.77	-0.71	-0.70	-0.54	0.77	-0.89	-0.26	-0.20
HE	0.66	0.71	-0.77	-0.71	-0.54	0.71	-0.77	-0.09	0.14
HF	0.14	0.14	-0.26	0.26	-0.03	0.83	-0.77	-0.26	0.83

Values in **bold** indicate significant correlations ($p < 0.05$). Abbreviations are defined in Table 2.