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A B S T R A C T

The aim of this investigation was to quantify the differences in torque steadiness and variability of the muscular control in children with cerebral palsy (CP) and typically developing (TD) children. Fifteen children with CP (age = 14.2 ± 0.7 years) that had a Gross Motor Function Classification System (GMFCS) score of I-III and 15 age and gender matched TD children (age = 14.1 ± 0.7 years) participated in this investigation. The participants performed submaximal steady-state isometric contractions with the ankle, knee, and hip while surface electromyography (sEMG) was recorded. An isokinetic dynamometer was used to measure the steady-state isometric torques while the participants matched a target torque of 20% of the subject's maximum voluntary torque value. The coefficient of variation was used to assess the amount of variability in the steady-state torque, while approximate entropy was used to assess the regularity of the steady-state torque over time. Lastly, the distribution of the power spectrum of the respective sEMG was evaluated. The results of this investigation were: 1) children with CP had a greater amount of variability in their torque steadiness at the ankle than TD children, 2) children with CP had a greater amount of variability at the ankle joint than at the knee and hip joint, 3) the children with CP had a more regular steady-state torque pattern than TD children for all the joints, 4) the ankle sEMG of children with CP was composed of higher harmonics than that of the TD children.

1. Introduction

Nearly four out of every 1000 children born in the United States has cerebral palsy (CP) (Yeargin-Allsopp et al., 2008), which is caused by a defect or lesion in the immature brain (Paneth & Kiely, 1984). The total lifetime economic burden to society is estimated to be nearly one million dollars per child with CP (CDC, 2004). A major portion of these costs comes from orthopedic surgeries and therapies focused on ameliorating the motor impairments seen in these children (CDC, 2004).

Children with CP generally have poor neuromuscular control and balance due to weak muscular strength, spasticity, and contractures (Woollacott & Shumway-Cook, 2005). Predominantly, the clinical literature has alluded that strength training can remedy the motor control impairments seen in these children. Although it has been clearly demonstrated that children with CP can improve their strength with strength training, the improvements in the motor control are often mixed, and in some cases can accentuate the biomechanical gait deficits (Damiano & Abel, 1998; Damiano, Arnold, Steele, & Delp, 2010; Damiano, Kelly, & Vaughn, 1995). This wide range of outcomes may occur because children with CP present a wide variety of sensorimotor abnormalities and compensation strategies (Mockford & Caulton,

2008). Additionally, it is possible that force- generating capacity of the musculature is not directly related to motor control of movement patterns.

The influence of structural musculoskeletal abnormalities (i.e., abnormal skeletal torsions or contractures) on the movement patterns of children with CP is fairly well understood; however, the motor control deficits present remain less understood. It has been established that increased fluctuations in force during a steady contraction are related to poor motor control in adults (Christou, 2011; Christou & Tracy, 2006); however, this relationship remains largely unknown in children with CP. A recent study by Bandholm, Rose, Slok, Sonne-Holm, and Jensen (2009) evaluated the steady-state isometric torques (i.e., the torques generated during a muscle contraction in which the joint angle and muscle length do not change) generated by the ankles of typically developing (TD) children and children with CP. Their results showed that children with CP have greater variability in their submaximal isometric torques during both dorsiflexion and plantarflexion compared with TD children. Hence, it is likely that the damaged central nervous system of children with CP also contributes to increases in variability of the motor output. Further exploration of the variations found in the performance of the muscles and the motor output has the potential to shed further light on the nature of the motor control deficits seen in these children. Muscular control of the joint movements requires proper activation of the corticospinal tracts (CSTs). Damage to these tracts in children with CP that have a spastic diplegic presentation commonly occurs in the periventricular area (Staudt, Pavlova, Bohm, Grodd, & Krageloh-Mann, 2003). Somatotopic organization of the lower extremity in the CST suggests that since the distal lower-extremity tracts are closer to the ventricle they more vulnerable to perinatal damage than those of the proximal lower-extremity (Staudt et al., 2003). This implies that more distal muscles may exhibit greater impairment in children with CP; however, few studies have explored differences in distal and proximal motor control. A recent study by Fowler and colleagues has noted an increasing proximal to distal motor control impairment in children with CP (Fowler, Staudt, & Greenberg, 2010). However, these observations were based on a clinical observational score. Further quantitative comparisons of the severity of reduced motor control and muscle activation may provide a more detailed understanding of the differences in motor control seen in children with CP.

The overall purpose of this investigation was to quantify the differences in the torque steadiness and variability of the muscular control in children with CP and TD children. The experiment conducted in this study was directed at addressing the following questions: 1) is torque steadiness in children with CP different from TD children? 2) is variability of the muscular control in children with CP different from TD children? 3) is the motor output of the distal muscles more variable than proximal muscles in children with CP? 4) is the maximum torque generated by the ankle, knee and hip of children with CP less than TD children?.

2. Methods

2.1 Subjects

Fifteen children with a diagnosis of either spastic diplegic (i.e., lower limb involvement) (n = 10) or hemiplegic (i.e., involvement on one side of the body) (n = 5) CP (age = 14.2 ± 0.7 years; height = 1.61 m; weight = 52.65 kg) that have a Gross Motor Function Classification System (GMFCS) score of I–III participated in this investigation (Olney & Wright, 2006). A number of neurologic factors contribute to the resulting type of CP, however, the different types do not necessarily result in differences in the severity of the involvement. By using the GMFCS we were able to ensure that the children were at similar levels of functionality, thus both spastic diplegic and hemiplegic children were included. Additionally, we separated the data based on type of CP and found no statistical differences. Therefore, both types of CP were grouped together for all statistical analyses. Seven children had a GFMCS score of I, five children had a GMFCS score of II, and three children had a GMFCS score of III. Children classified as level I can walk without limitations, children classified as level II have limitations walking long distances and may wear

orthotics, and children classified as level III require a hand-held mobility device such as a walker or forearm crutches to assist in ambulation (Palisano et al., 1997). The children with GMFCS level III who participated in this experiment were high functioning children who used forearm crutches to assist in ambulation. Additionally, 10 of the children used ankle-foot orthotics.

An additional fifteen age and gender matched TD children (age = 14.1 ± 0.7 years; height = 1.64 m; weight = 56.88 kg) participated in this investigation and served as a control group. Both the parent and child verbally confirmed that the TD children had no known neurological conditions. Of the children with CP, 13 were Caucasian and 2 were African American. Additionally, 13 of the TD children were Caucasian, 1 was African American, and 1 was Asian American. Additional subject demographics are listed in Table 1. All testing was done at the University of Nebraska Medical Center, and was approved by the Institutional Review Board.

2.2 Experimental design

The subjects performed a submaximal steady-state isometric contraction with the ankle, knee, or hip while surface electromyography (sEMG) was recorded. An isokinetic dynamometer (Biodex Inc., Shirley, NY) was used to measure the steady-state isometric torques generated by the ankle plantar flexors, knee extensors, and hip extensors. The children with spastic diplegic CP used the less involved leg to ensure that the child could match the target value and were able to maintain the steady-state contraction for a sufficient duration. Alternatively, the children with hemiplegic CP used their hemiplegic side. The TD children performed the motor tasks with their dominant leg. To determine which is the dominant leg, these children were asked to kick a ball, and the leg that was used to kick was used for the testing.

Table 1
Demographics of subjects, where M = male and F = female.

Cerebral palsy		Typically developing	
Age	Gender	Age	Gender
18	M	18	M
17	M	17	M
17	M	16	M
17	M	16	M
16	M	16	M
16	F	16	F
16	F	15	F
14	M	14	M
13	M	14	M
13	M	13	M
13	F	13	F
13	F	12	M
12	M	11	M
10	F	11	F
8	M	9	M

The largest torque generated from two maximum isometric contractions was used to establish the child's maximum voluntary torque (MVT) at the respective joints. Maximum torque was normalized by body weight (kg) prior to comparison. The child then performed two steady-state isometric contractions at 20% of their MVT. This value was determined by pilot investigation which determined that children with CP had difficulty in reliably sustaining a steady-state isometric contractions below 20% MVT. The target and the torque exerted by the child was displayed as a bar graph on a large monitor that was positioned ~1 meter away from the subject at eye level. The child was given ample time to practice achieving the target torque before the two actual trials were recorded. These two trials were then averaged together for all data measures. The voltage output from the torque motor was read by custom LabVIEW (National Instrument Inc., USA) software and sampled at 1 kHz by a 14-bit National Instruments analogue-to-digital converter. The voltage output from the Biodex dynamometer was converted to Nm and displayed in real-

time as a bar graph in the custom software interface. The maximum on the vertical scale of the bar graph was twice the target value (Kouzaki & Shinohara, 2010). Each steady-state contraction was performed for 30 s while the sEMG was simultaneously collected.

For the ankle plantarflexion task the children were seated with the knee extended and ankle at 90°. During the knee extension task the children were seated with the hip and knee at 90°. During the hip extension task the children were supine with the hip at 90°. Between each 30 s contraction the children had approximately 30 s of rest, and between each of the test conditions the children received about 1 minute of rest while the appropriate attachment for the next test condition was connected to the Biodex dynamometer. Additionally, the order of the task conditions was randomized and the protocol was well tolerated, with all subjects able to complete the tasks.

The coefficient of variation (CV = [standard deviation of torque/mean torque] x 100) was used to assess the amount of variability present in the middle 15 s of the steady-state torque. A lower CV value was an indication of greater motor control of the joint steady-state torque (Christou & Tracy, 2006). Approximate entropy (ApEn) was also calculated to assess the regularity of the middle 15 s of the steady-state torque. ApEn evaluates the likelihood that similar patterns in the time series will be present at a later time period. The ApEn calculation results in a score ranging from 0 to 2, a value closer to zero indicated that the time series had a more consistent pattern, while a value closer to 2 indicated a less consistent pattern. ApEn was calculated using the following equation:

$$\mathrm{ApEn}(N, m, r) = \ln\left[\frac{C_m(r)}{C_{m+1}(r)}\right] \quad (1)$$

where *N* was the number of data points in the time series, m was the number of points compared, r was the similarity criterion based on the standard deviation of the data series, and C was the number of self similar vectors defined by m points based on the r criterion. Similar to previous investigation of the structural variability present in a physiological time series, m was 2, and r was 20% of the standard deviation of the time series (Ivkovic & Kurz, 2011; Pincus, 1991; Stergiou, Buzzi, Kurz, & Heidel, 2004).

When using ApEn to analyze the structural variations of a time series, one assumes that the distance between the data points were due to changes in the behavior of the system, and not due to the data points being neighbors in time (Ivkovic & Kurz, 2011; Provenzale, Smith, Vio, & Murante, 1992). Data points can be neighbors in time if high sampling rate was used to monitor changes in the state of the system. When this occurs the structural variations in the time evolving dynamics will artificially appear to be self-similar. This investigation used a method of delays to overcome the possibility that the sampling rate used to measure the steady-state torque values could influence the quantified structural variations. An average mutual information algorithm was used to determine a time delay (T_i) for the points that were used to assess changes in the steady-state torque dynamics (Abarbanel, 1996). Eq. (2) presents the average mutual information algorithm where *T* is the time delay, *x(t)* is the original steady-state torque data, *x(t + T)* is the time delay data, *P(x(t), x(t + T))* is the joint probability for measurement of *x(t)* and *x(t + T), P(x(t))* is the probability for measurement of *x(t),* and *P(x(t + T))* is the probability for measurement of *x(t + T).*

$$I_{x(t),x(t+T)} = \sum P(x(t), x(t+T)) \log_2\left[\frac{P(x(t), x(t+T))}{P(x(t))P(x(t+T))}\right] \quad (2)$$

Average mutual information was iteratively calculated for various time delays, and the selected time delay was the first local minimum of the iterative process. The time delay at this local minimum has been shown to be effective for providing unique information about changes in the system's dynamic (Abarbanel, 1996).

sEMG was measured as the participant performed the isometric contractions with the ankle and knee joints. During the ankle plantar flexion conditions the gastrocnemius was measured, and during knee

extension conditions the vastus lateralis was measured. Pilot investigation revealed that during the hip extension conditions the sEMG signal of the gluteus maximus did not exceed the noise band of the sEMG signal during the 20% MVT contractions for TD adults. Thus, no sEMG was measured during the hip extension conditions. The signals from the sEMG electrodes were wirelessly transmitted to a Delsys amplifier and were sampled at 1 kHz by a 14-bit National Instruments analogue-to-digital converter.

The sEMG was band-pass filtered at 20–300 Hz, and a fast Fourier transform algorithm was used to calculate the power spectral density of the signal. The median of the power spectrum was calculated by determining the harmonic (i.e., the frequency components of the signal) for 50% of the cumulative power spectral distribution. Since the power spectrum distribution is often skewed, the median of the power spectral density is an indication of where the majority of the power is located in the signal, and can be used to determine whether the signal is primarily composed of higher or lower harmonics.

The power spectral densities for the respective sEMG were also normalized to the maximum frequency found in the power spectrum, and the spectrum was partitioned into 50 Hz frequency bins from 0 to 300 Hz. Thus, 6 bins were created. The amount of power in the respective bins was integrated to determine their contribution to the overall power. Changes in the power in the respective bins may indicate different activation patterns of the motor units by the CSTs for controlling the steady-state contraction.

2.3 Statistical design

Separate mixed model (group x joint) ANOVAs with a Tukey post hoc were used to examine the differences between the children with CP and TD children for the maximum torque, CV, ApEN and median of the power spectrum. Additional mixed model ANOVAs (group x bin) with Tukey post hoc were used to examine the differences in the harmonics that comprise the muscle activation of the gastrocnemius and vastus lateralis for the CP and the TD children. All comparisons were made at the 0.05 alpha level, and all results are presented as mean ± standard error of the mean.

3. Results

3.1 Steady-state isometric torques

There was a significant group main effect for the CV, with children with CP having a greater amount of variability in their steady-state isometric torque than TD children ($F(1,28) = 12.8$; $p = 0.001$; Fig. 1). This result indicated that the overall lower extremity steady-state isometric torques were more variable in the children with CP. A representative time series is shown in Fig. 2. Qualitatively it is apparent that the child with CP is more variable. There was also a significant joint main effect for CV ($F(2,56) = 3.9$; $p = 0.025$). Additionally, there was a significant joint x group interaction ($F(2,56) = 4.8$; $p = 0.012$). The post hoc tests indicated that the amount of variability in the steady-state torque of the ankle of children with CP was significantly different than the TD children ($p < 0.05$; Fig. 3). However, there were no significant differences in the amount of variability in the steady-state isometric torque at the knee (CP = 8.3 ± 2.3%, TD = 3.3 ± 0.5%; $p > 0.05$) and the hip joints (CP = 6.92 ± 2.19%, TD = 2.73 ± 0.54%; $p > 0.05$) of the two groups.

In the children with CP, significant differences were seen between the CV of the ankle and the CV of the knee ($p < 0.05$; Fig. 3). Likewise, differences also existed between the CV of the ankle and the CV of the hip ($p < 0.05$; Fig. 3). However, no significant differences were seen between the CV of the knee and the CV of the hip ($p > 0.05$).

The mean time lag was 234.94 ± 6.79. There was a significant group main effect for the ApEn ($F(1,28) = 45.6$; $p < 0.001$; Fig. 4). This indicated that the children with CP had a more regular steady-state torque pattern than TD children for all the joints. There was also a significant joint main effect for the

ApEn (F(2,56) = 6.1; p = 0.004). However, we did not find a significant joint x group interaction (F(2,56) = 1.0; p = 0.382).

3.2 Electromyography

Examination of the sEMG revealed that there was a significant group main effect for the median of the power spectrum (F(1,27) = 9.6; p = 0.005; Fig. 5). This indicated that the overall power spectrum from the respective muscles of the children with CP were composed of higher harmonics. There was also a significant joint main effect for the median of the power spectrum (F(1,27) = 92.1; p < 0.001). However, we did not find a significant joint x group interaction (F(1,27) = 0.7; p = 0.424).

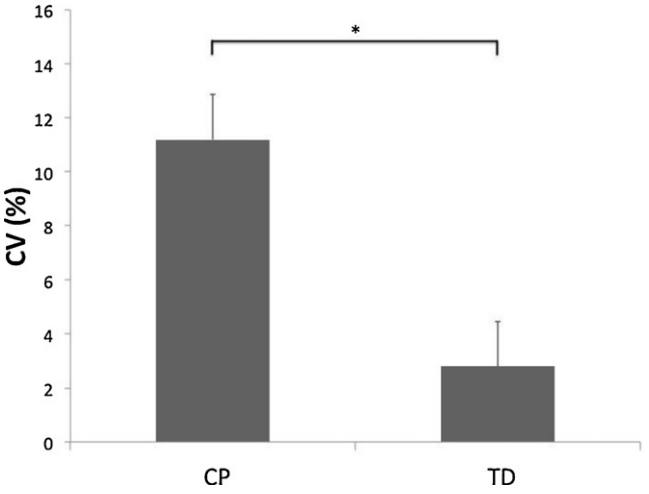

Fig. 1. Coefficient of variation across all joints for the CP and TD groups. *p < 0.05.

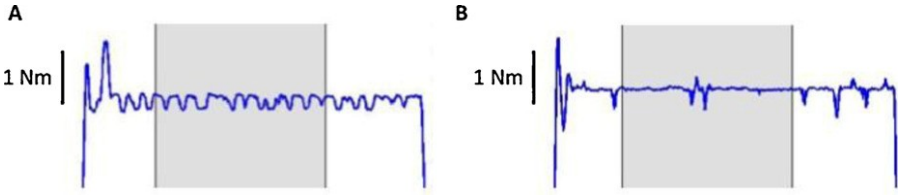

Fig. 2. Exemplary time series showing ankle joint torques for (A) a child with CP and (B) a TD child. The grayed area represents the 15 s of the steady-state contraction that was evaluated.

Examination of the harmonics that comprise the vastus lateralis sEMG showed a significant group effect for the amount of power in the power spectrum (CP = 2.09 ± 0.14; TD = 1.57 ± 0.13; F(1,27) = 7.8; p = 0.01). This indicated differences between the groups in the total amount of power in the vastus lateralis sEMG signal. There was also a significant bin main effect for the amount of power in the power spectrum (F(5,135) = 237.9; p < 0.001). Furthermore, a significant bin x group interaction (F(5,135) = 6.5; p < 0.001) was also seen. The post hoc tests revealed that the vastus lateralis of the children with CP had greater power in the 51– 150 Hz range compared to TD children (p < 0.05; Fig. 6).

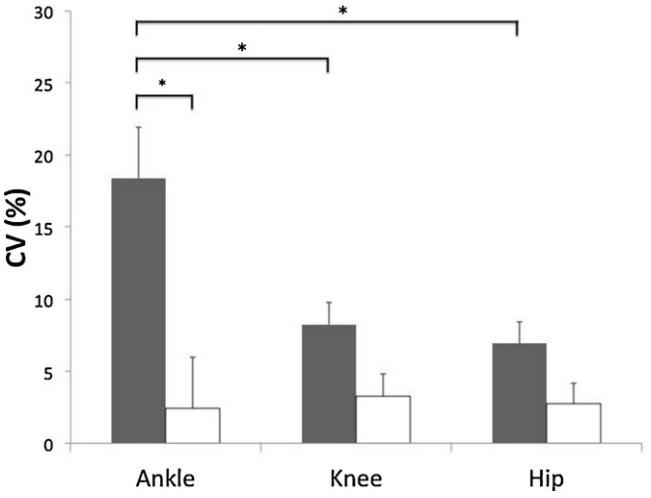

Fig. 3. Coefficient of variation for the ankle, knee, and hip for the CP group (black) and the TD group (white). *$p < 0.05$.

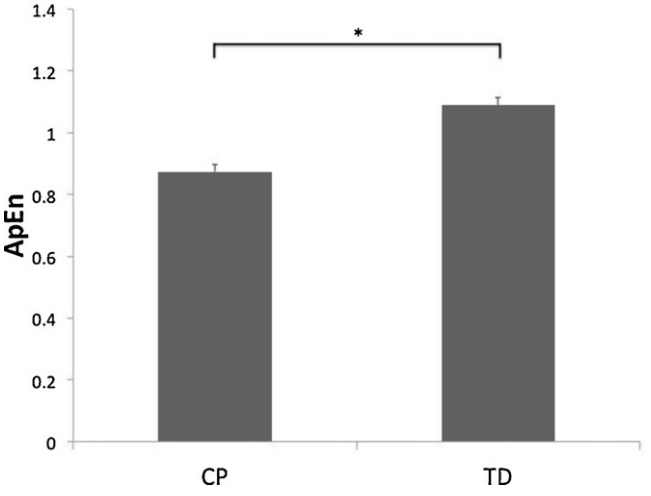

Fig. 4. Average approximate entropy for the ankle, knee, and hip for the two groups. *$p < 0.05$.

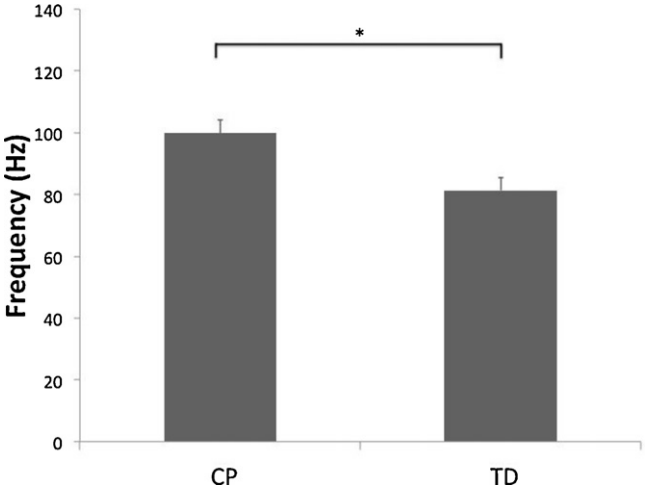

Fig. 5. Average median of the power spectrum for the sEMG of the vastus lateralis and gastrocnemius for the two groups. *$p < 0.05$.

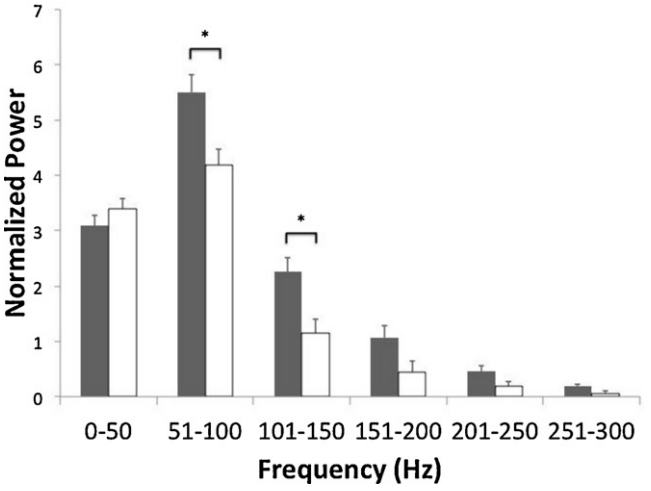

Fig. 6. Normalized power for the sEMG of the vastus lateralis in each of the 50 Hz bins for the CP group (black) and TD group (white). *$p < 0.05$.

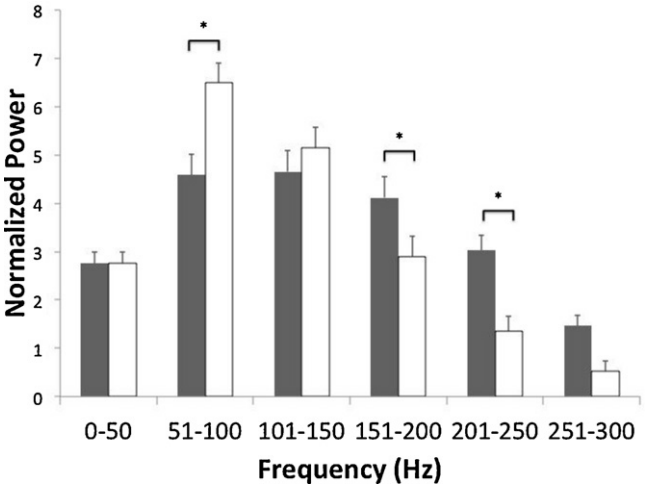

Fig. 7. Normalized power for the EMG signal of the gastrocnemius in each of the 50 Hz bins for the CP group (black) and TD group (white). *$p < 0.05$.

The harmonics that comprise the gastrocnemius sEMG signal showed no significant group effect for the amount of power across the power spectrum ($F(1,27) = 0.5$; $p > 0.05$). However, there was a significant bin main effect for the amount of power across the power spectrum ($F(5,135) = 72.9$; $p < 0.001$). Additionally, there was a significant bin x group interaction ($F(5,135) = 10.9$; $p < 0.001$). This indicated that although the total amount of power was the same for the children with CP and the TD children, the distribution of the power was different. The post hoc tests revealed that the TD children had a greater amount of power in the 51–100 Hz range, while the children with CP had a greater amount of power in the 151– 250 Hz range ($p < 0.05$; Fig. 7).

3.3 Maximum torque

There was a significant group main effect for the normalized maximum torque ($F(1,28) = 33.1$; $p < 0.001$), indicating that the TD children generated greater maximum torques across all joints combined compared to the children with CP (Fig. 8). There was also a significant joint main effect for the normalized maximum torque ($F(2,56) = 19.6$; $p < 0.001$). However, there was no significant joint x group interaction ($F(2,56) = 0.3$; $p = 0.715$), indicating that the isometric torques for the ankle (CP = 0.35 ± 0.05 Nm/kg; TD = 1.03 ± 0.10 Nm/kg), knee (CP = 0.91 ± 0.08 Nm/kg; TD = 1.53 ± 0.10 Nm/kg) and hip (CP = 0.76 ± 0.10 Nm/kg; TD = 1.30 ± 0.16 Nm/kg) were similar between the two groups.

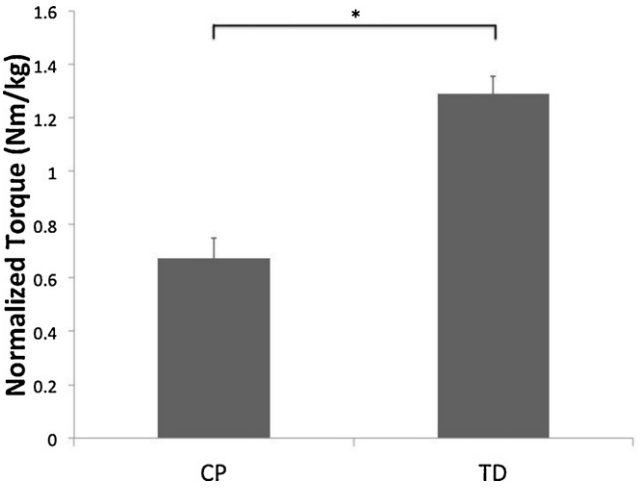

Fig. 8. Normalized maximum torque averaged across all joints for the CP group and TD group. *$p < 0.05$.

4. Discussion

4.1 Steadiness of isometric joint-torques

Overall our results imply that children with CP have greater difficulty in controlling the lower extremity joints during a low level steady-state isometric motor task. This notion was supported by a larger coefficient of variation for the lower extremity isometric torques of the children with CP. This result further confirms that the children with CP have a reduced control of the lower leg antigravity musculature. Additionally, this result is likely due to the damage in the CST. However, Hoon and colleagues (2009) previously identified that damage to the thalamocortical pathways that are involved in the sensorimotor integration processes influence the isometric force generation capacity of children with CP. Hence, it is possible that the lack of steadiness in the isometric lower extremity joint torques seen in this investigation may also be related to the integrity of the thalamocortical pathways.

Our results also demonstrated that the impaired motor control in the children with CP was most evident in steady-state isometric performance of the ankle joint. This result corroborates with what has been previously reported by Bandholm and colleagues (2009). However, we found no differences between the two groups at the knee or hip joint. This contrasts the results of Engsberg, Wagner, Reitenbach, Hollander, and Standeven (2001) who found adults with CP to have greater variability at the knee than typical adults. However, it is important to note differences in the two paradigms that were used to assess the influence of CP on motor control. Engsberg and colleagues used an isokinetic knee extension task while we used a low level isometric steady-state contraction. Thus, it is possible that children with CP have greater control of the low level contractions at the hip and knee, but the impairments in the voluntary control of the respective joints are exacerbated during dynamic contractions. Alternatively, it is also possible that the differences between these two studies arise from differences in the age of the participants.

Our results additionally showed that the amount of variability present in the ankle steady-state torques were greater than the amount of variability in the hip and knee joint steady-state torques, which implies that children with CP have greater distal motor impairments. Similar results have been reported from clinical tests that have evaluated the selective voluntary control of the lower extremities in children with CP (Fowler et al., 2010). Contrary to this notion, we found no differences between the amount of variability at the hip and knee in the children with CP. Potentially, two factors may have accounted for the reason that the knee joint was not more variable than the hip. For one, this investigation included

hemiplegic children whose presentation may not be due to damage in the periventricular area. Secondarily, it is possible that the remaining participants may not have extensive enough perinatal damage to significantly affect the corticospinal tracts that serve the knee and hip musculature. However, without the use of brain imaging techniques, such as diffusion tensor imaging, the relationship between motor control and structural damage remains speculative.

In addition to examining the amount of variability, we also explored the regularity of the variability present in the steady- state joint torques during the 15 s. Our results showed that the TD children had a less regular pattern than the children with CP across all lower extremity joints. This may indicate that although the children with CP had a greater amount of variability in the joint torque, these variations in the steady-state torque were repeated more often. This may mean that there is less flexibility in the motor output used to maintain the steady-state contraction. Alternatively, this may indicate less flexibility in recruiting various motor units to be involved in sustaining the contraction. This concept appears to align with the optimal variability model put forth by Stergiou, Harbourne, and Cavanaugh (2006). This model has the shape of a quadratic function (e.g., $-x^2$) with optimal variability located at the local maximum. Deviations to the left of this maximum represent an increase in the noise that comprises the movement variability, while deviations to the right of the maximum represent an increase in periodicity or regularity. The model proposes that if the variations are too regular the system is more rigid and less adaptable. Based on the optimal variability model, our results may suggest that the steady-state joint torques of children with CP were shifted toward a more regular state, and may have been less adaptable.

4.2 Electromyography

In examining the harmonics of the sEMG for the ankle plantarflexion and knee extension tasks we found that the children with CP had a greater median of the power spectrum when the joints were combined. This indicates that overall the sEMG of children with CP were composed of higher harmonics than TD children. Previous experimental work has noted that the force variability of isometric contractions performed by children with CP is composed of greater amount of noise (Chu & Sanger, 2009). Based on this experimental evidence, we suspect that a shift towards higher harmonics may indicate a greater amount of noise in the overall performance motor units of the children with CP. Alternatively, the higher harmonics may be an indication of alterations in the motor command that results in a different coupling or firing patterns of the respective motor units.

At the knee we found that children with CP have a greater amount of overall power between 51 and 150 Hz in the sEMG signal of the vastus lateralis. Previous studies have noted that children with CP have an inability to properly activate and synchronize the available motor units during isometric contractions (Rose & McGill, 2005). Hence, it is possible that the increase in power in the 51–150 Hz range may reflect this difficulty.

Although the total amount of power was the same for the two groups for the gastrocnemius, the distribution of the power was quite different. The TD children had a greater amount of power between 51 and 100 Hz, while the children with CP had a significantly greater amount of power between 151 and 250 Hz. This result indicates that the sEMG of the gastrocnemius of children with CP was shifted towards the higher harmonics. A considerable amount of evidence exists to suggest that noise permeates every level of the nervous system, which can be problematic for information processing (Faisal, Selen, & Wolpert, 2008). Since children with CP have more noise in their steady-state isometric contractions (Chu & Sanger, 2009), it is probable that the higher harmonics may represent similar characteristics in the children that participated in this investigation. We suspect that the poor signal-to-noise properties of the nervous system of children with CP may reside in the integrity of the CST that transmits the descending motor command to the respective motor units. Alternatively, it is possible that the shift toward higher harmonics seen in children with CP is an indication of a different activation of the motor units in the children with CP rather than just noise in the motor command.

4.3 Maximum isometric joint torque

Overall we found that the maximum isometric torques generated by the lower extremity joints were lower in the children with CP. This result concurs with what has been previously reported in the literature (Damiano et al., 1995; Wiley & Damiano, 1998). However, we did not find differences at the specific lower extremity joints. It is possible that this is in part due to the different presentations of the children with CP who participated in this investigation. In other words, where one child may present a strength deficit at the knee, they may compensate for this deficit by having an increased amount of strength at another joint in the kinematic chain. Several investigations have previously recognized the compensation strategies used by children with CP, and have summed the isometric force values generated by the respective lower extremity joints to quantify the overall weakness of the lower extremity joints (Damiano & Abel, 1998; Hoon et al., 2009).

5. Conclusions

Overall our results imply that children with CP have greater difficulty in controlling the lower extremity joints during a low level steady-state isometric motor task. Our results also demonstrated that the impaired motor control in the children with CP was most evident in steady-state performance of the ankle joint, implying that children with CP have greater distal motor impairments. Additionally, we found children with CP have a more regular pattern than TD children across all the lower extremity joints possibly indicating less flexibility in the motor output. We also found that the maximum isometric torques generated by the lower extremity joints were lower in the children with CP. These results show that the motor output of the lower extremity joints of children with CP is more variable, which we suspect may contribute to the walking impairment seen in these children.

It remains unclear whether these control problems reside in the musculature, spine, and peripheral nervous system of the child, or possibly at the cortical level. We plan to explore these possibilities in the future. Additionally, this study demonstrated that it is possible to quantify the motor control deficits in children with CP. This may provide a way to evaluate the efficacy of current therapeutic techniques used to treat children with CP. Ideally the amount of variability seen in children with CP should be reduced after therapy, possibly indicating an increase in motor control. Using this paradigm we may be able to determine the efficacy of different therapeutic techniques.

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