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Original Research

Children With Cerebral Palsy Show Higher Static—But Not Higher Dynamic—Motor Fatigability in Grip and Pinch Tasks Than Children With Typical Development Do

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Abstract

Objective. The purpose of this study was to investigate differences in static and dynamic motor fatigability during grip and pinch tasks between children with unilateral spastic cerebral palsy (USCP) and children with typical development (TD) and between preferred and nonpreferred hands.

Methods. Fifty-three children with USCP and 53 age-matched children with TD (mean = 11 years 1 month; SD = 3 years 8 months) participated in 30-second maximum exertion sustained and repeated grip and pinch tasks. For sustained tasks, the Static Fatigue Index and the ratio of mean force between the first and last thirds of the curve were calculated. For repeated tasks, the ratio of mean force and the ratio of numbers of peaks between the first and last thirds of the curve were calculated.

Results. Higher Static Fatigue Index scores for grip and pinch were found with USCP in both hands and between hands in both groups. Dynamic motor fatigability showed inconsistent results, with higher levels of fatigability in children with TD than in children with USCP for grip in the ratio of mean force between the first and last thirds of the curve in nonpreferred hands and in the ratio of number of peaks between the first and last thirds of the curve in preferred hands.

Conclusion. Higher motor fatigability in children with USCP than in children with TD was found for static but not dynamic grip and pinch. Underlying mechanisms may play different roles in static and dynamic motor fatigability.

Impact. These results highlight that static motor fatigability in grip and pinch tasks should be part of a comprehensive upper limb assessment and that this could be the target of individualized interventions.

Keywords: Cerebral Palsy, Fatigue, Hand Strength, Motor Fatigability, Muscle Strength

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Introduction

Cerebral palsy, the most common cause of motor difficulties in children, has an incidence of 0.2% globally,[1] 20% to 30% of which have unilateral spastic cerebral palsy (USCP).[1] Use of the nonpreferred limb in activities of daily living is often impaired.[2,3] Muscle weakness contributes considerably, caused by smaller cross-sectional areas or difficulties recruiting additional motor units or coordinating muscles.[3–5] Reliable measurement instruments for upper limb strength in children with USCP are available.[2,6–9]

Studies on muscle weakness in children with USCP have focused on submaximal or maximum voluntary contractions of 3 to 5 seconds.[6,7,10] However, sustained strength is important for ADL.[11] Here, we define inability to sustain strength as motor fatigability (MF), "the magnitude or rate of change of motor performance . . . after any type of voluntary activity or exercise."[12,13] MF can occur with sustained tasks (static MF [SMF]) or repeated tasks (dynamic MF [DMF]). In multiple sclerosis, there is widely varied research into upper limb MF,[14–16] but similar research in USCP is scarce and with disparate results.[17–19]

Only 3 studies have investigated SMF using maximum strength protocols in children with USCP and young adults. Van Meeteren et al used the Static Fatigue Index (SFI) during a 20-second maximum grip strength protocol in 26 young adults with USCP and 26 controls, concluding that USCP participants showed higher MF than controls in both hands but no difference between hands.[20] Hong et al used a 1-arm continuous lifting test with preset resistance until fatigue in 6 children with USCP, using multiscale entropy analyses of electromyography measures. Decreased muscle fiber conduction velocity was shown, indicating more MF in children with USCP than in children with typical development (TD).[21] Furthermore, increased motor unit synchronization, another indicator of MF, was found in children with USCP. However, Doix et al, investigating MF using submaximal elbow flexion against constant load until failure in children with USCP, found values like those in children with TD.[10] Also, in children with USCP, there was a lower increase in electromyography amplitude but no difference with controls for median frequency decrease or acceleration variation increase. Similar discrepancies have been found for legs in children with USCP.[22] Thus, differences in protocols and outcome measures may produce different results, and measurement instruments with good clinimetric properties are required to investigate MF in this population.[10,18,20,21,23,24] Recently, test–retest reliability of new MF protocols (used here) in children with TD has been investigated, with promising results.[24]

We investigated MF differences between children with USCP and children with TD and differences between both hands within each group, using sustained and repeated grip and pinch protocols, to look for differences in SMF and DMF between children with USCP and children with TD and between preferred and nonpreferred hands in these groups. Based on SMF and DMF, we expected children with USCP to show more MF than children with TD. Also, we expected nonpreferred hands to show more MF than preferred hands in both groups. Results should provide insights into MF in children with USCP, possibly helping optimize their treatment.

Methods

Participants

A convenience sample of 60 children with USCP and 60 children with TD was invited to participate between January 2019 and July 2020 from different regular and special education schools, hospitals, and clinical research programs in Belgium, the Netherlands, and the United States. Children were included in the USCP arm if they were diagnosed with USCP; were between 6 and 18 years old; were able to understand the instructions; were Dutch or English speaking; agreed to participate; and were judged at Gross Motor Functioning Classification System level I, II, or III or Manual Ability Classification System level I, II, or III.[25] Children with USCP were excluded if they had participated in strength training of the upper limb in the past 6 months, had surgery on the upper limbs in the last 6 months, had botulinum toxin injections in the last 6 months in their upper limbs, or had severe contractures in their upper limbs making it impossible to perform the grip and pinch strength tasks.

Children with TD were included if they were between 6 and 18 years old, were able to understand the instructions, were Dutch or English speaking, and were motivated to participate. Children with TD were excluded if they had any type of upper limb motor disorder (neurological and/or orthopedic). The preferred hand of the children with TD was compared with the less-affected hand in children with USCP, and the nonpreferred hand of the children with TD was compared with the more affected hand in the children with USCP. For consistency, we further refer to preferred and nonpreferred hands for both children with USCP and children with TD.

Descriptive information included age, sex, preferred/nonpreferred hand, and Manual Ability Classification System level (for children with USCP only). Children and parents gave written informed consent prior to the measurements. This research was approved by the Medical Ethical Committee of Hasselt University (CME2018/069), Maastricht University (2019–1168), and Teachers College, Columbia University (New York, NY, USA) (IRB 13–220).

Measurements

Two testers with extensive experience in the clinical evaluation of children with USCP and trained in these tests performed the measurements following a detailed, standardized protocol. The same methods were used as in Brauers et al.[26] A detailed log was written after the testing of each child to describe any irregularities during measurement.

All measurements were performed with the Biometric E-link H-500 Hand Kit (Biometrics Ltd, Newport, UK), comprising dynamometer and pinch meter. Forces are shown in kilograms. The handle position of the dynamometer was adjusted according to hand size. Out of 3 predetermined positions, the width was adjusted so that the end of the handlebar approximated the distal end of the metacarpals. The dynamometer and pinch meter were not additionally supported by the tester. For all strength and fatigability measures, children used the same position. They sat in an adjustable chair, back against the backrest, feet flat on the floor, arms leaning on an armrest, elbows bent at 90 degrees, with a neutral wrist position; there was no support of the shoulder. This protocol has been adopted from Brauers et al and has been found reliable

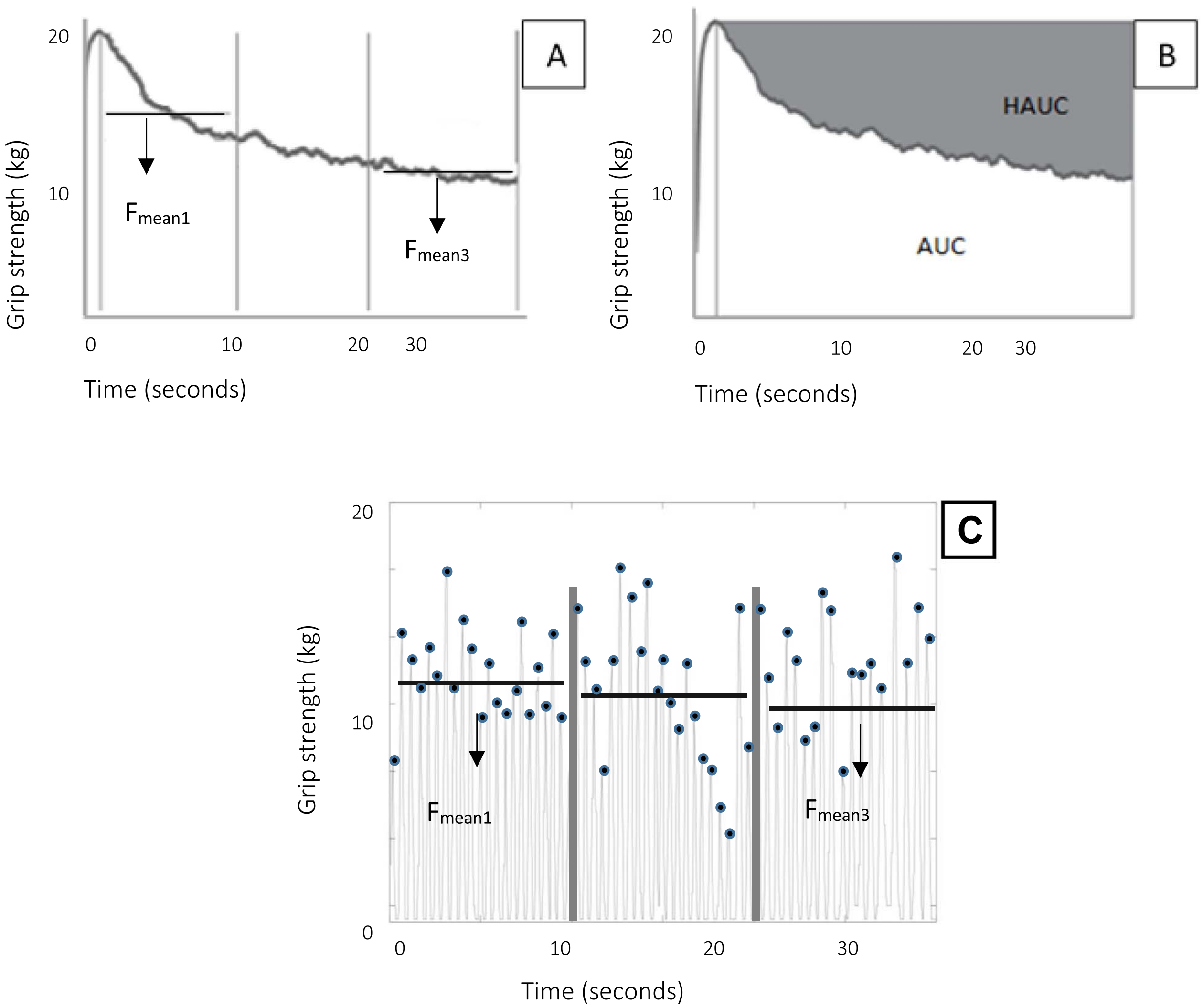

Figure 1. (A) Calculation of ratio of mean force between the first and last thirds of the curve. The continuous horizontal line represents the mean force for the first third of the curve (F_{mean1}) and the mean force for the last third of the curve (F_{mean3}). (B) Schematic representation of the areas used to calculate the Static Fatigue Index. (C) Calculation of ratio of mean force between the first and last thirds of the curve and ratio of numbers of peaks between the first and last thirds of the curve. Circles represent peaks; horizontal lines represent mean forces. F_{mean1} = mean force for the first third of the curve; F_{mean3} = mean force for the last third of the curve. AUC = area under the force-time curve; HAUC = hypothetical AUC.

in children with TD, with intraclass correlation coefficients (ICCs) ranging between 0.69 and 0.91.[24]

To measure SMF, one 30-second maximum sustained contraction with each of the dynamometer and pinch meter was performed, always starting with the preferred hand. Children were told: "I will count 3, 2, 1 and then you are going to squeeze as hard as possible and keep on squeezing until I tell you to stop squeezing." These instructions were standardized across testers, and feedback on the remaining time (but not on the amount of force exerted) was shown for the child on a PC screen. The test was considered successful if the child reached his/her peak force within the first 10 seconds of the force-time curve. If a test was considered invalid due to not reaching peak force in the first 10 seconds or because of lack of concentration, 2 consecutive tests could be performed, each with a rest period of 5 minutes in between. Whether the child showed sufficient concentration was judged by the examiner based on the clinical experience in testing children with cerebral palsy. For example, when a child was distracted by a person walking into the room or when he/she started talking during the squeezing task, which caused dual-task interference, we performed a second trial. After 3 invalid trials, no additional trial was done. An example of a force-time curve for this 30-second maximum exertion protocol is shown in Figure 1A and B.

DMF was also measured with a 30-second maximum exertion protocol but with repeated contractions. Children squeezed as hard and as frequently as possible over a 30-second period, and a successful measurement was indicated if the child squeezed at any pace over the entire 30 seconds. Again, instructions were standardized across testers. If a trial was considered invalid, 2 consecutive trials could be administered and so on. An example of a force-time curve for the dynamic protocol is shown in Figure 1C.

Outcome Measures

SMF was quantified using 2 parameters: the ratio of mean forces (Ratio-F_{mean}) and the SFI. By calculating Ratio-F_{mean}, more information becomes available on the decrease of force in the first and last thirds of the curve than if the entire curve is included. Ratio-F_{mean} (in kilograms) was calculated in 3 steps: first, the peak force in the first 10 seconds of the curve was identified, and the time prior to this was excluded from calculations; second, the remaining curve was divided into 3 equal parts, and the mean force for the first third (F_{mean1}) and the mean force for the last third (F_{mean3}) were calculated (Fig. 1A); and third, the ratio between mean forces for the first and last thirds of the curve was calculated using the following equation: Ratio-F_{mean} = ($F_{mean1} - F_{mean3}$)/F_{mean1}. Higher MF is indicated by a decrease in mean force over time, resulting in a positive Ratio-F_{mean} closer to 1 (the maximum possible value). The SFI was calculated in 3 steps[27,28]: first, the peak force in the first 10 seconds of the curve was identified, and the curve prior to this was excluded; second, an area under the force-time curve (AUC) and a hypothetical AUC were calculated (the hypothetical AUC represents a situation in which strength would have been sustained at a maximal level during the total trial (ie, zero MF); and third, the SFI was calculated using the following equation: SFI = 100 × [1 − (AUC/hypothetical AUC)] (Fig. 1B). A higher SFI indicates a higher SMF.[27,28] The relevant parameters for SMF are shown in Figure 1A and B.

To calculate DMF, 2 outcome parameters were calculated: Ratio-F_{mean} and the ratio of numbers of peaks (Ratio-N_{peaks}). For these, the entire 30-second force-time curve was used in contrast to the SMF calculation where the time to peak force is excluded. This is because with DMF no such peak force can be determined. The curve was divided into 3 equal parts. The F_{mean1}, F_{mean3}, and numbers of peaks for the first third (N_{peaks1}) and the last third (N_{peaks3}) were calculated. The ratios were then calculated from the following equations: Ratio-F_{mean} = ($F_{mean1} - F_{mean3}$)/F_{mean1} and Ratio-N_{peaks} = ($N_{peaks1} - N_{peaks3}$)/N_{peaks1}. A decrease from the first third to the last third of the curve in either Ratio-F_{mean} or Ratio-N_{peaks} results in a positive ratio (maximum possible value = 1), indicating the degree of DMF. An example of a DMF curve is shown in Figure 1C.

Data Analysis

Descriptive statistics are presented for the participants (age, sex, preferred/nonpreferred hand, Manual Ability Classification System levels, maximum grip/pinch strength) with number of participants and, depending on the outcome, mean and SD or median and interquartile range.

To ensure good-quality data, curves were visually rechecked to ensure they met the criteria of a successful performance prior to data analysis. This was because it was sometimes difficult to see whether the peak force in SMF trials was actually reached within the first 10 seconds. To recap, SMF trials were excluded if peak force did not fall within the first 10 seconds of the curve; DMF trials were excluded if the child was unable to squeeze repeatedly at any pace during the 30 seconds. If a trial was invalid based on these criteria, that single trial was excluded from the database. Other trials of the same child, if valid, were still included. Furthermore, for DMF trials, individual peaks in the dynamic measurement were defined by a drop of force between putative peaks of at least 50% of the foregoing peak.

Normality of the data was investigated both statistically (using the Shapiro–Wilk test, skewness, and kurtosis) and visually (using histograms). To meet the assumption of normal distribution, a log transformation of Ratio-N_{peaks} in pinch strength was used for further analysis.

Independent *t* tests were used to investigate differences between children with USCP and children with TD. To separately investigate the differences between the preferred hand and the nonpreferred hand in each group, paired-sample *t* tests were used. A Bonferroni correction was added to correct for multiple comparisons by a factor of 1/k, where k is the number of hypotheses in our study. The adjusted significance level was set at $P < .006$. All statistical analyses were performed using SPSS Statistics 25 (IBM SPSS, Armonk, NY, USA).

Results

Participants

Of the 60 children invited in each arm, 56 children with USCP and 60 children with TD agreed to participate. Three children with USCP were not able to perform all tests due to severe muscle weakness, resulting in a sample of 53 children with USCP. Because children were age matched afterward, the final sample included 53 children with USCP and 53 children with TD. Descriptive statistics are shown in Table 1.

Differences Among Children With USCP and Children With TD

All outcomes for SMF and DMF are shown in Tables 2 and 3. The Supplementary Table provides more details on the parameters of static and dynamic measurements for the first and third parts of the trial.

Not all children were able to perform all tests due to muscle weakness or coordination problems. Table 2 reports the numbers of children with USCP and children with TD for each condition. Significantly higher SMF was found in children with USCP than in children with TD for the SFI using grip and using pinch in the nonpreferred hand (*P* values between .0001 and .001) (Fig. 2A and B). For the preferred hand, significant differences were found in the SFI for grip but trending toward significance for pinch ($P = .0001$ for grip; $P = .007$ for pinch) (Fig. 2A and B). For Ratio-F_{mean}, a nonsignificant difference between children with USCP and children with TD was found for pinch in the preferred hand ($P = .036$) (Fig. 2C and D). For Ratio-F_{mean} grip in both hands and Ratio-F_{mean} pinch in the nonpreferred hand, no significant differences were found ($P = .129$) (Fig. 2C and D).

For DMF, significantly higher values were found in children with TD than in children with USCP for Ratio-F_{mean} for grip in the nonpreferred hand ($P = .001$) and for Ratio-N_{peaks} for grip in the preferred hand ($P = .002$) (Fig. 3A and B). For other outcome measures, no significant differences between hands were found (Fig. 3C and D).

Differences Between Preferred Hand and Nonpreferred Hand

All results regarding differences between preferred and nonpreferred hands in both groups are shown in Table 3. In the group of children with USCP, significantly higher SMF was found in the nonpreferred than in the preferred hand for SFI in both grip and pinch (SFI grip: $P = .002$; SFI pinch: $P = .001$) (Fig. 2A and B). Ratio-F_{mean} did not show significant differences between the hands (grip: $P = .316$; pinch: $P = .441$) (Fig. 2C and D).

For DMF in children with USCP, significantly higher values were found in the nonpreferred hand for Ratio-F_{mean} for pinch strength ($P = .001$) but not for grip strength ($P = .755$) (Fig. 3A and B). For Ratio-N_{peaks}, no significant differences

Table 1. Descriptive Statistics for Included Children With USCP and Children With TD[a]

Characteristic	USCP (n = 53)	TD (n = 53)
Age, mean (SD)	11 y 1 mo (3 y 8 mo)	11 y 1 mo (3 y 8 mo)
Preferred hand (left/right)	31/22	6/47
Sex, men/women	27/26	33/20
MACS level, I/II/III	15/33/5	
Maximum grip strength of preferred hand, kg, mean (SD)	16.6 (1.3)	20.4 (1.4)
Maximum grip strength of nonpreferred hand, kg, mean (SD)	7.1 (1.0)	18.8 (1.4)
Maximum pinch strength of preferred hand, kg, mean (SD)	4.4 (0.3)	4.6 (0.3)
Maximum pinch strength of nonpreferred hand, kg, mean (SD)	2.2 (0.3)	4.4 (0.3)

[a]MACS = Manual Ability Classification System; TD = typical development; USCP = unilateral spastic cerebral palsy.

Table 2. SMF and DMF of Children With USCP and Children With TD and Statistical Comparisons Between Groups[a]

Motor Fatigability	Hand	Parameter	USCP (n = 53)				TD (n = 53)				*df*	*t*	*P*
			Mean (SD)	Minimum	Maximum	n	Mean (SD)	Minimum	Maximum	n			
Static	Nonpreferred	SFI grip	58.83 (14.99)	33.28	93.37	47	43.87 (13.97)	22.85	91.29	51	97	5.141	.0001[b]
		SFI pinch	55.23 (16.83)	16.38	88.59	48	42.72 (12.41)	19.76	79.79	50	97	4.237	.0001[b]
		Ratio-F_{mean} grip	0.34 (0.19)	−0.09	0.89	45	0.29 (0.18)	−0.06	0.68	49	93	1.752	NS
		Ratio-F_{mean} pinch	0.30 (0.35)	−0.35	0.74	17	0.29 (0.15)	−0.18	0.73	21	37	−0.77	NS
	Preferred	SFI grip	49.28 (16.40)	30.38	93.58	47	38.88 (12.46)	13.72	78.77	51	97	3.57	.001[b]
		SFI pinch	45.91 (11.69)	18.54	75.32	48	39.70 (10.85)	21.55	84.57	50	97	2.74	NS
		Ratio-Fmean grip	0.31 (0.14)	0.04	0.79	40	0.32 (0.17)	0.11	0.66	47	86	0.194	NS
		Ratio-F_{mean} pinch	0.35 (0.25)	−0.29	0.93	31	0.25 (0.14)	−0.45	0.52	33	63	1.854	NS
Dynamic	Nonpreferred	Ratio-F_{mean} grip	0.27 (0.29)	−0.48	0.81	44	0.35 (0.16)	−0.03	0.69	45	88	−1.65	.001[b]
		Ratio-F_{mean} pinch	0.32 (0.17)	−1.00	0.90	42	0.25 (0.25)	−0.47	0.69	43	84	1.621	NS
		Ratio-N_{peaks} grip	0.11 (0.18)	−0.50	0.50	45	0.15 (0.14)	−0.29	0.39	44	88	−1.18	NS
		Ratio-N_{peaks} pinch	−0.04 (0.28)	−1.00	0.99	41	0.05 (0.16)	−0.36	−0.18	43	83	−1.87	NS
	Preferred	Ratio-F_{mean} grip	0.30 (0.21)	−0.29	0.76	44	0.40 (0.14)	−0.14	0.78	45	88	−2.58	NS
		Ratio-F_{mean} pinch	0.16 (0.24)	−0.93	0.67	42	0.26 (0.23)	−3.78	0.76	45	86	−1.98	NS
		Ratio-N_{peaks} grip	−0.01 (0.32)	−1.29	0.36	44	0.09 (0.16)	−0.45	0.38	46	89	−1.87	.002[b]
		Ratio-N_{peaks} pinch	0.11 (0.20)	−0.89	0.65	42	0.12 (0.18)	−0.18	0.79	45	86	−0.1	NS

[a]DMF = dynamic motor fatigability; NS = not significant; Ratio-F_{mean} = ratio of mean force between the first and last thirds of the curve; Ratio-N_{peaks} = ratio of numbers of peaks between the first and last thirds of the curve; SFI = Static Fatigue Index; SMF = static motor fatigability; TD = typical development; USCP = unilateral spastic cerebral palsy. [b]Significant difference at $P < .006$.

Table 3. SMF and DMF of Children With USCP and Children With TD and Statistical Comparisons Between Hands[a]

Group of Children	Motor Fatigability	Parameter	Preferred Hand		Nonpreferred Hand		*df*	*t*	*P*
			Mean (SD)	n	Mean (SD)	n			
USCP	Static	SFI grip	49.27 (16.39)	24	58.83 (14.99)	23	46	3.203	.002[b]
		SFI pinch	45.91 (11.69)	25	55.22 (16.82)	22	46	3.664	.001[b]
		Ratio-F_{mean} grip	0.32 (0.16)	18	0.36 (0.18)	12	29	−0.353	NS
		Ratio-F_{mean} pinch	0.35 (0.27)	18	0.32 (0.31)	18	35	−1.018	NS
	Dynamic	Ratio-F_{mean} grip	0.30 (0.22)	21	0.25 (0.31)	20	40	−0.738	NS
		Ratio-F_{mean} pinch	0.13 (0.29)	21	0.26 (0.33)	20	40	2.005	.001[b]
		Ratio-N_{peaks} grip	−0.04 (0.32)	21	0.04 (0.22)	21	42	1.558	NS
		Ratio-N_{peaks} pinch	0.07 (0.27)	18	0.05 (0.29)	21	38	−0.256	NS
TD	Static	SFI grip	38.88 (12.46)	26	43.87 (13.97)	26	51	3.575	.001[b]
		SFI pinch	39.70 (10.85)	26	42.71 (12.40)	26	51	2.824	NS
		Ratio-F_{mean} grip	0.32 (0.17)	22	0.29 (0.18)	21	42	1.520	NS
		Ratio-F_{mean} pinch	0.24 (0.17)	25	0.28 (0.16)	24	48	1.002	NS
	Dynamic	Ratio-F_{mean} grip	0.39 (0.16)	26	0.35 (0.16)	24	49	−1.122	NS
		Ratio-F_{mean} pinch	0.16 (0.63)	27	0.23 (0.27)	23	49	0.736	NS
		Ratio-N_{peaks} grip	0.08 (0.17)	25	0.15 (0.14)	25	49	3.440	.002[b]
		Ratio-N_{peaks} pinch	0.15 (0.15)	25	0.06 (0.21)	23	47	−3.230	NS

[a]NS = not significant; Ratio-F_{mean} = ratio of mean force between the first and last thirds of the curve; Ratio-N_{peaks} = ratio of numbers of peaks between the first and last thirds of the curve; SFI = Static Fatigue Index; TD = typical development; USCP = unilateral spastic cerebral palsy. [b]Significant difference at $P < .006$.

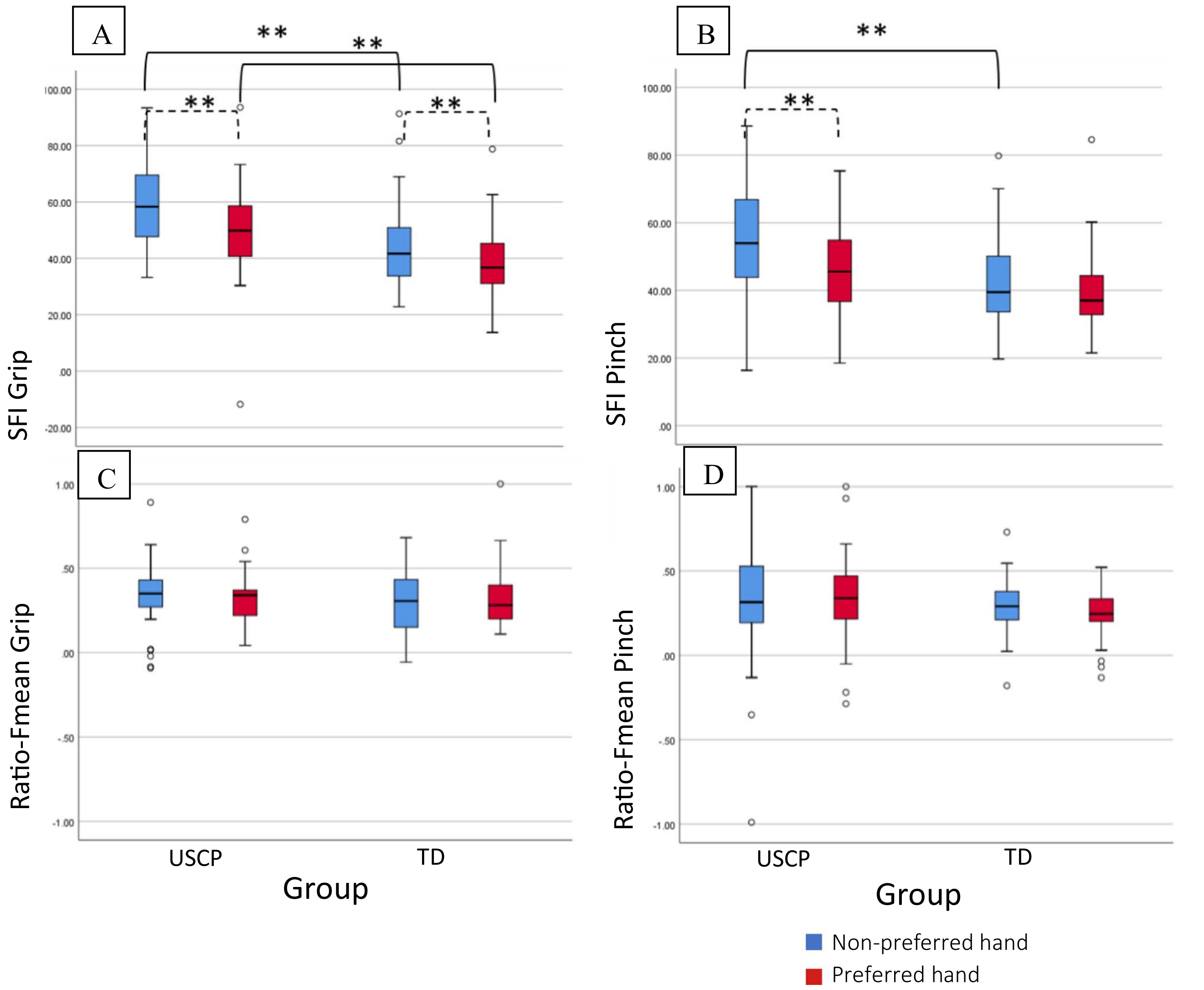

Figure 2. Results of the Static Fatigue Index (SFI) and ratio of mean force between the first and last thirds of the curve (Ratio-F_{mean}) for static motor fatigability. **Significant at the level of $P < .006$. TD = typical development; USCP = unilateral spastic cerebral palsy.

were found between the hands for grip ($P = .079$) or pinch ($P = .023$) (Fig. 3C and D).

Among children with TD, significantly higher SMF was found in the nonpreferred than in the preferred hand for grip (SFI grip: $P = .001$) and a trend toward significance using pinch (SFI pinch: $P = .007$) (Fig. 2A and B). There was no significant difference between the hands for Ratio-F_{mean} (grip: $P = .321$; pinch: $P = .197$) (Fig. 2C and D). For DMF, Ratio-N_{peaks} showed significantly higher values for grip in the nonpreferred hand ($P = .002$) and a nonsignificant difference in the preferred hand ($P = .032$) (Fig. 3C and D). For Ratio-F_{mean} in DMF, no significant differences were found (grip: $P = .054$; pinch: $P = .759$) (Fig. 3A and B).

Discussion

General Summary

This study investigated differences in SMF and DMF between children with USCP and children with TD, and the differences between hands in each group, using SMF (sustained) and DMF (repeated) grip and pinch tasks. Significantly higher SMF was found in children with USCP than in children with TD based on the SFI in both hands. For DMF, mostly nonsignificant differences were found for Ratio-F_{mean} and Ratio-N_{peaks} in both hands using grip and pinch, with a trend toward higher values in children with TD. Within each group, SFI indicated higher SMF in the nonpreferred hand. However, for DMF, results were less consistent but pointed toward higher MF in the nonpreferred hand.

Differences Between Children With USCP and Children With TD

Between groups, significantly higher SMF was found in children with USCP than in children with TD based on the SFI, in line with Van Meeteren et al.[20] They investigated MF using a 20-second maximum grip strength protocol in both hands and calculated the SFI.[20] Higher MF levels in children with USCP than in children with TD may result from centrally originating problems such as difficulty activating additional motor units during strenuous activities, leading to inability to fully activate muscles and losing strength over time.[10] Van Meeteren et al also reported mean SFI values of 32% for grip in the nonpreferred hand in children with USCP,

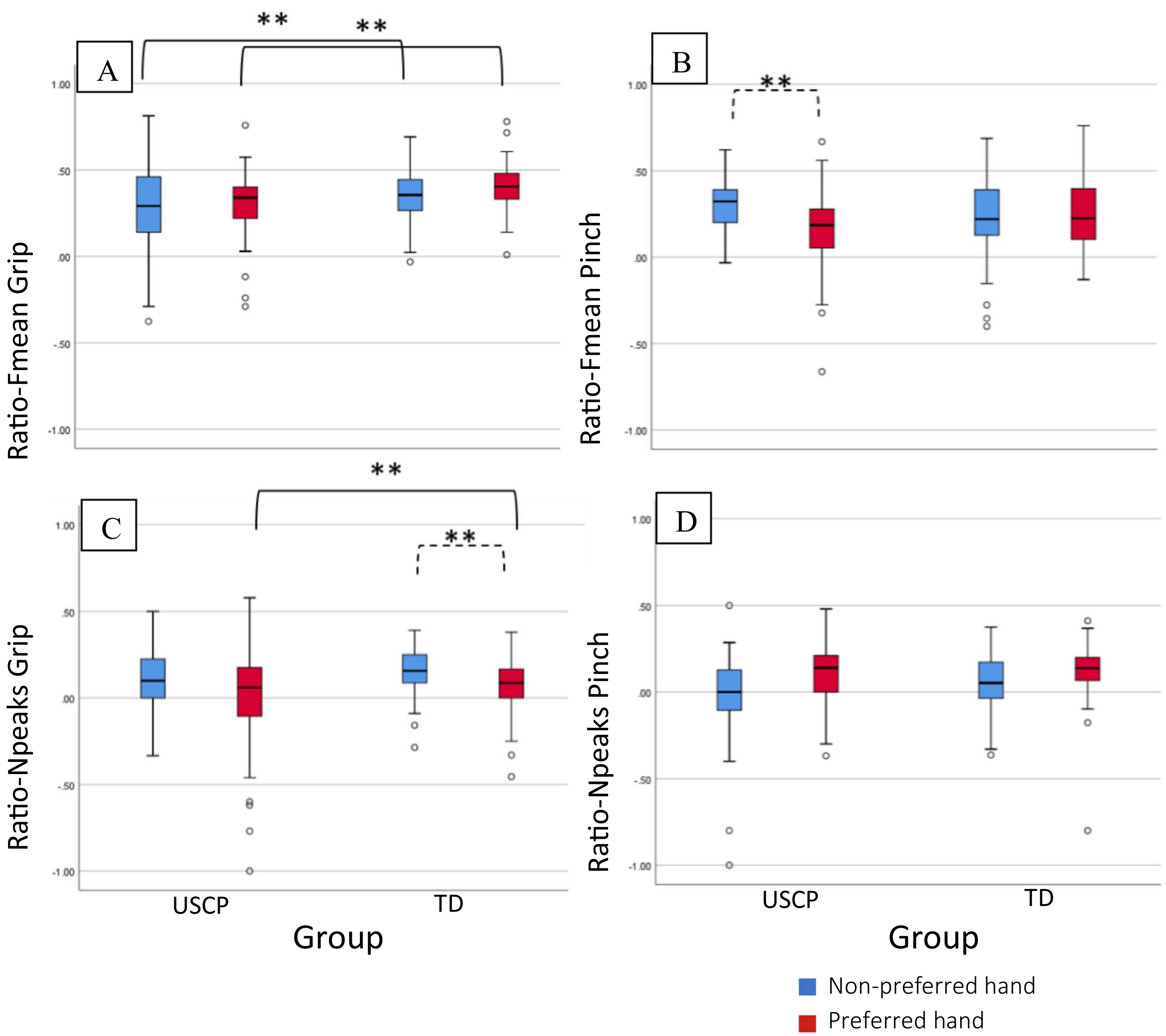

Figure 3. Results of the ratio of mean force between the first and last thirds of the curve (Ratio-F_{mean}) and ratio of numbers of peaks between the first and last thirds of the curve (Ratio-N_{peaks}) for dynamic motor fatigability. **Significant at the level of $P < .006$. TD = typical development; USCP = unilateral spastic cerebral palsy.

whereas we found values of 55% to 60%. This difference may attributable to their 20-second protocol, where our 30-second test is able to provoke more pronounced fatigability levels. Future research might investigate the nature of decline in force during the last third of the force-time curve as attempted with the newly developed Ratio-F_{mean}. However, whereas the SFI showed significant differences between groups, the Ratio-F_{mean}, as proposed in this study, did not. The expectation that Ratio-F_{mean} would provide with additional information about the decline in force from the first third to the last third of the curve was not met due to high variability after peak force was reached. Statistically, this variability affects Ratio-F_{mean} more than SFI, explaining its inability to discriminate between groups.

For DMF, most comparisons showed no differences, but there was significantly higher DMF in children with TD based on Ratio-N_{peaks} using grip in the preferred hand and on Ratio-F_{mean} grip in the nonpreferred hand. This is in line with previous research investigating MF during repeated submaximal elbow flexion and extension.[10] The comparable or inconclusive results may be explained by, first, children with USCP having relatively more slow-twitch fatigue-resistant muscle fibers; second, children with lower maximum strength values showing less fatigue because the intramuscular pressure is lower, reducing restriction of blood flow[29]; and third, children with USCP possibly underperforming dynamically, being unable to activate all motor units during a maximum voluntary contraction, meaning that they perform submaximally and thus do not fatigue as much.[5] A smaller number of peaks in children with USCP might have resulted in a smaller decline in the numbers of peaks. In this case, reduced ability to contract and release constrains performance and does not provoke fatigability. Gordon et al investigated time to peak and to release in children with USCP and children with TD during grip tasks,[30] concluding that, in children with USCP, both times were increased in both hands because of motor cortex and corticospinal pathway lesions and genetic changes in muscle tissue.[31,32] Differences between groups became more pronounced with increasing speed and accuracy of movement, as in our study.[30] Furthermore, excitability of the ipsilateral corticospinal projections has been associated with fatigue in a study by Wrightson et al using the Pediatric Quality of Life Inventory Version 3.0 for Cerebral Palsy.[33] Differences in corticospinal tract excitability often alters the precision of sensory predictions, altering fatigue sensations in children with USCP, leading to our inconclusive results.[33]

Fatigability Laterality

For children with USCP, the SFI showed significantly higher SMF in the nonpreferred hand, possibly caused by deficits in recruitment in the nonpreferred limb.[10] These differences between hands in recruitment patterns in cerebral palsy may also result from atypical development of the corticospinal tracts,[33] with pruned ipsilateral projections from the less-affected hemisphere leading to worse motor performance in the nonpreferred hand.[34,35]

For DMF, most outcomes showed no significant differences between hands in children with USCP, in line with the study of Hong et al investigating MF in upper limb cyclic lifting tasks.[21] However, in our study, there was significantly higher DMF in the nonpreferred hand for Ratio-F_{mean} and a trend toward higher DMF in the preferred hand for Ratio-N_{peaks}, both using pinch. These inconsistent results may be explained by the large SDs in both outcome measures. Other studies on DMF also show conflicting results for the lower limbs, such as that of Eken et al, who concluded that MF levels were specific to certain muscles or muscle groups.[22] When walking at self-selected speeds, there was higher MF in the nonpreferred leg for 3 muscles and in the preferred leg for 1 muscle.[22] This indicates that there may be more or less MF depending on the type of task (static, dynamic, or more functional). Also, results may be different for preferred and nonpreferred limbs, including upper limbs, as in our study. In daily life, the nonpreferred hand is often used less due to developmental disregard in children with USCP. This may also mean that the hand is less trained than the preferred hand and thus shows more MF.[36] Conversely, if the nonpreferred hand is used less to manipulate objects, making it less able to grasp and release as fast as the preferred hand, this may cause submaximal performance in the dynamic task, shown by the number of peaks, and thus less evidence of MF.[11] However, because these results are inconclusive, conclusions in this should be taken with caution.

In the TD group, there was significantly higher SMF in the nonpreferred hand based on the SFI but not on the ratio of mean force. Additionally, there were trends toward differences between the hands of children with TD for the numbers of peaks in DMF but not for the ratio of mean force. However, the results on which hand showed higher DMF were contradictory. These results on the direction of DMF, that is, higher or lower, in the preferred and nonpreferred hands in both children with USCP and children with TD may be explained by the way that MF is expressed in the dynamic protocol. Here, fatigability may be expressed both as a decrease in the number of peaks, indicating lower speed in contracting and relaxing muscles, and a decrease in maximum strength, meaning a decrease in force output. Individual factors could result in 1 child decreasing more in number of peaks and another decreasing more in muscle strength. Future research should investigate whether the idea of a trade-off between speed of contraction and maximum strength may result in more insights into MF in either hand of both groups. Published research on such a trade-off in goal-directed movements indicates that children use different strategies to compensate for fatigability. Some are able to move faster while preserving movement accuracy but with a greater co-contraction of muscles around the joint, thus using more energy. However, others move more slowly, with less co-contraction, thus using less energy but with a decline in movement accuracy.[37] This idea of a trade-off may help with our understanding of coordinating co-contraction strategies to preserve energy, a potentially interesting aspect to investigate with our protocol for DMF.

Several aspects in the methodology of this study should be considered. First, children were tested in several schools and countries, resulting in different measurement conditions. However, children were always tested in a familiar environment, not distracted by background noises. Furthermore, although every precaution has been taken to minimize variability between the 2 testers, slightly different ways of administering the tests are always possible. However, the extensive experience of our testers should reduce this effect in our study.

Second, the current study did not investigate the origin of MF. Future research should look at underlying mechanisms of MF in children with USCP, such as recruitment patterns, lesion timing, or lesion patterns. This could be investigated using a combination of the SMF and DMF protocols as well as surface electromyography or transcranial magnetic stimulation techniques. By doing this, the relation between MF and connectivity patterns, motor unit recruitment, and structural muscular changes could be investigated.[3–5,38–40] In addition, the relation between MF and maximum strength, spasticity, or selectivity should be investigated to elucidate the effect of MF in activities of daily living. Future research should investigate the effects of higher maximum strength levels on the MF levels in children with USCP.

Children with unilateral spastic cerebral palsy showed significantly higher static motor fatigability in both hands than children with typical development in grip and pinch tasks according to the SFI. However, results for dynamic motor fatigability are inconsistent, with a trend toward higher dynamic motor fatigability in typically developing children. Additionally, within groups, higher static motor fatigability was found in the nonpreferred hands, but, again, results for dynamic motor fatigability were inconclusive. The results of this study indicate that static motor fatigability is impaired in unilateral spastic cerebral palsy, but further research is needed on the origin of motor fatigability and its impact on daily life in these children.

Author Contributions

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Ethics Approval

This research was approved by the Medical Ethical Committee of Hasselt University (CME2018/069); Maastricht University (2019–1168); and Teachers College, Columbia University, in New York (IRB 13–220).

Data Availability

Data supporting the findings of this study are available from the corresponding author on request.

Disclosures

The authors completed the ICMJE Form for Disclosure of Potential Conflicts of Interest and reported no conflicts of interest.

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