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# Children and adolescents with cerebral palsy flexibly adapt grip control in response to variable task demands

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ABSTRACT

*Background:* Children and adolescents with cerebral palsy demonstrate impairments in grip control with associated limitations in functional grasp. Previous work in cerebral palsy has focused on grip control using relatively predictable task demands, a feature which may limit generalizability of those study results in light of recent evidence in typically developing adults suggesting that grip control strategies are task-dependent. The purpose of this study was to determine whether and how varying upper extremity task demands affect grip control in children and adolescents with cerebral palsy.

*Methods:* Children and adolescents with mild spastic cerebral palsy ($n = 10$) and age- and gender-matched typically developing controls ($n = 10$) participated. Participants grasped an object while immersed in a virtual environment displaying a moving target and a virtual representation of the held object. Participants aimed to track the target by maintaining the position of the virtual object within the target as it moved in predictable and unpredictable trajectories.

*Findings:* Grip control in children with cerebral palsy was less efficient and less responsive to object load force than in typically developing children, but only in the predictable trajectory condition. Both groups of participants demonstrated more responsive grip control in the unpredictable compared to the predictable trajectory condition.

*Interpretation:* Grip control impairments in children with cerebral palsy are task-dependent. Children and adolescents with cerebral palsy demonstrated commonly observed grip impairments in the predictable trajectory condition. Unpredictable task demands, however, appeared to attenuate impairments and, thus, could be exploited in the design of therapeutic interventions.

## 1. Introduction

During active object manipulation, successful grasp requires individuals to adapt grip force (GF) to the weight and changing inertial forces of the held object (i.e., load force; LF). While initial studies of GF-LF coupling suggested that GF is continuously modulated in-phase with changing LF (Blank et al., 2001; Flanagan and Wing, 1993; Viviani and Lacquaniti, 2015), recent studies of grip control in typically developing (TD) adults indicate that GF-LF coordination patterns are flexibly organized as a function of task demands (Grover et al., 2018; Grover et al., 2019a; Grover et al., 2019b; Grover et al., 2020). Participants in those studies shifted from more continuous (i.e., strongly coordinated and responsive) to more intermittent (i.e., less responsive) GF-LF coupling when the magnitude of LFs experienced at the point of grasp decreased (Grover et al., 2018, 2019) and when task requirements involved more predictable upper extremity (UE) movements and, thus, more predictable LF variations (Grover et al., 2019a). An important lesson from these studies is that it is critical to systematically vary task demands to reveal the full range of grip control strategies.

This lesson may be particularly important for efforts to characterize grip control impairments that result from pathology, like cerebral palsy (CP). Grip control in children with CP has been previously examined during the performance of sequential lifts involving a single, predictable UE trajectory (i.e., grip-lift-hold) (Duff and Gordon, 2003; Eliasson et al., 1992; Gordon and Duff, 1999). GF in the affected hands of children with CP has been characterized as excessive (i.e., greater force production) and less responsive to LF changes compared to TD peers, with a GF-LF coordination pattern resembling that of infants less than one year old (Eliasson et al., 1991). It is unknown if CP-related grip impairments occur under less predictable task conditions, which

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are known to promote more continuous GF-LF coupling in TD adults (Grover et al., 2019a). Additionally, previous findings of an apparent lack of GF-LF coordination in CP (e.g., Eliasson et al., 1992) may reflect differences in UE kinematics between children with CP and TD children. In that study (see their Fig. 2D, in particular the 400 g condition), children with CP produced lower UE accelerations than TD children. Because LF is proportional to acceleration, this means they experienced lower LF than TD children. The apparent non-responsiveness of GF to changing LF observed in children with CP may, therefore, be related to reduced task demands (i.e., lower LF), since lower LFs are associated with more intermittent (i.e., non-responsive) GF-LF coupling in TD adults compared to higher LFs (Grover et al., 2018, 2019a, 2019b).

The present study was designed to determine whether and how the demands imposed on UE kinematics affect grip control in children and adolescents with CP. We used a virtual reality target tracking task (cf. Grover et al., 2019a) to control UE kinematics in order to create comparable patterns of LF for participants with CP and TD peers. The virtual target moved along unpredictable trajectories (more demanding and previously associated with more continuous GF-LF coupling; Grover et al., 2019a) or predictable trajectories (associated with more intermittent GF-LF coupling). We also manipulated mass of the grasped object; lower mass leads to lower LF and was previously associated with more intermittent GF-LF coupling (Grover et al., 2018). We hypothesized that differences in grip control between children with CP and TD children would be attenuated under conditions that promote more continuous GF-LF coupling in TD adults.

## 2. Methods

### 2.1. Participants

A convenience sample of 10 children and adolescents (7 M, 3F) between 8 and 16 years with mild spastic CP and 10 age- and gender-matched TD peers participated. Grip behavior in CP reaches mature patterns by 8 years (Gordon and Forssberg, 1997). Thus, only participants > 8 years were included. Participants with CP were recruited from a nonprofit academic pediatric medical center in the midwestern United States. Participants of Manual Ability Classification System (MACS) (Eliasson et al., 2006) levels I-III were recruited. Participants with CP were excluded due to blindness, deafness, or executive function impairment precluding the ability to participate. The single participant recruited of MACS level III was unable to grasp the object in a way allowing for accurate GF recording and was excluded from final analysis. Thus, our final sample with CP included participants with only mild impairments in hand function. TD controls had no documented physical disabilities. Parents provided written consent, and participants provided assent. The study was approved by the University of Cincinnati Institutional Review Board (USA). Sample descriptors are summarized in Table 1.

### 2.2. Materials & procedure

The procedure was adapted from Grover et al., 2019a. Participants grasped a custom 3-D printed object (Fig. 1a) with a radial-digital grasp pattern. Each participant was seated in a chair with posterior support and donned a CV1 Oculus Rift headset (Oculus, Menlo Park, CA, USA) which rendered a virtual room created with the Unity game engine (v.5.6, Unity Technologies, San Francisco, CA, USA) (Fig. 1b). Participants viewed a virtual representation of the held object, which we will hereafter refer to as the virtual object. The virtual environment also included two cylinders. A smaller yellow cylinder served as a target which participants aimed to track. A longer cylinder extended above and below the yellow cylinder, serving as a track tube for the target (Fig. 1b). The target moved along the track tube in two trajectory conditions: (1) predictable (i.e., sine waveform) and (2) unpredictable (i.e., smoothed fractional Brownian motion; fBm). The set of target trajectories was the same for each participant (Fig. 1c).

**Table 1**
Participant descriptors.

| Characteristic | CP ($n$ = 10) | TD ($n$ = 10) |
|---|---|---|
| | *Mean (SD)* | *Mean (SD)* |
| Age (y:mo) | 12:8 (3:4) | 12:4 (3:0) |
| Height (cm) | 154.18 (15.20) | 157.48 (22.81) |
| Body Mass (kg) | 46.76 (17.06) | 48.15 (21.33) |
| Maximum grip (kg) | | |
| Unaffected/dominant | 4.40 (1.82) | 5.04 (1.71) |
| Affected/nondominant | 2.80 (1.70) | 4.32 (1.33) |
| Reach (cm) | | |
| Unaffected/dominant | 53.8 (0.66) | 54.0 (0.76) |
| Affected/nondominant | 50.2 (0.74) | 54.1 (0.78) |
| Affected elbow flexion angle (degrees) | 1.5 (3.37) | NA |
| Edinburgh Handedness Score | + 8 (93.23) | + 90.3 (20.84) |
| | *Count (%)* | *Count (%)* |
| Handedness | | |
| Left | 5 (50) | 0 (0) |
| Right | 5 (50) | 10 (100) |
| Sex | | |
| Male | 7 (70) | 7 (70) |
| Female | 3 (30) | 3 (30) |
| Race/Ethnicity | | |
| African American | 1 (10) | |
| Asian | 1 (10) | |
| Caucasian | 8 (80) | 8 (80) |
| Hispanic | | 2 (20) |
| GMFCS level | | |
| I | 8 (80) | NA |
| II | 2 (20) | NA |
| MACS level | | |
| I | 7 (70) | NA |
| II | 2 (20) | NA |
| III | 1 (10) | NA |
| CP Distribution | | |
| Hemiplegia | 8 (80) | NA |
| Diplegia | 2 (20) | NA |

*Note.* Data are mean (SD) until row "Left" including and after which data are number of participants (percentage of participants). There were no significant differences between groups for demographic variables of age, height, weight, or reach, $p > .05$. CP, cerebral palsy; TD, typically developing; NA, not applicable; GMFCS, Gross Motor Function Classification System; MACS, Manual Ability Classification System.

Object motions were tracked via a magnetic motion-capture system at a sampling rate of 50 Hz (Polhemus Liberty; Polhemus Corp., Colchester, VT, USA). Positional data were streamed in real-time to Unity, providing participants with a virtual rendering of the object's motion. Participants aimed to maintain the position of the virtual object within the target as it moved within the track tube. The track tube color provided feedback regarding tracking accuracy. When performance was accurate, the track tube was blue, and error (i.e., displacement > 1/6 the length of the track tube) turned the track tube red. Trunk movements were not physically restricted but were monitored by the experimenter to ensure that participants maintained trunk contact with the chair's posterior support. Participants completed the experimental task with each hand.

GF was measured at 50 Hz using an FS20 low-force compression load cell (Measurement Specialties, Inc., Dayton, OH, USA) embedded in the held object under the participant's first digit. Ring weights were attachable to the object (Fig. 1a) to create two mass conditions: high-mass (180 g) and low-mass (100 g). We selected mass conditions that would elicit a possible difference while avoiding fatigue, as determined through piloting.

Participants completed three trials of each mass × trajectory condition per limb, resulting in 24 trials per participant. Trajectories were randomized, while mass and limb were blocked within each participant. Between participants, initial mass was randomized. Starting limb

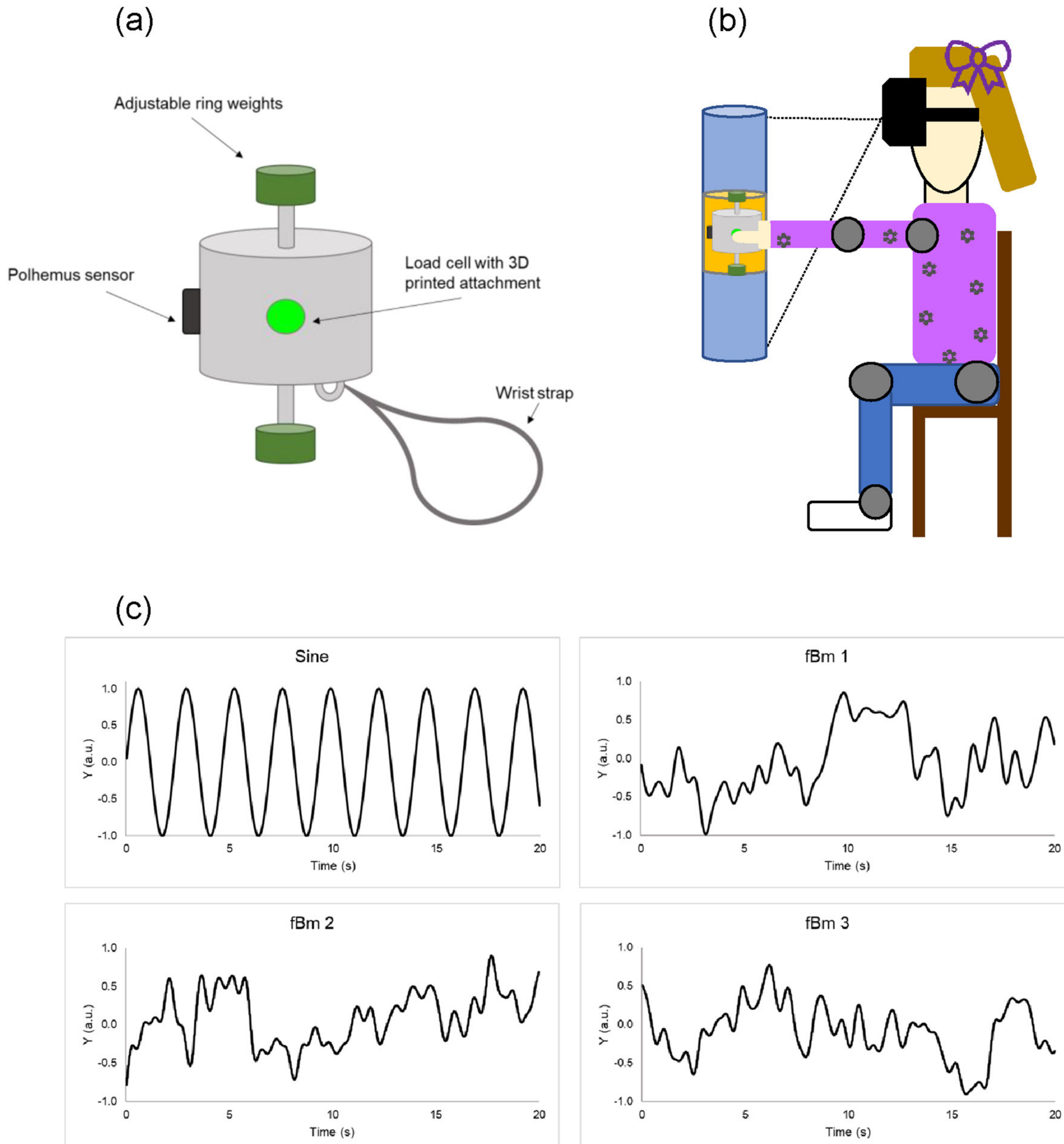


**Fig. 1.** (a) The held object with labeled components. The object was comparable in size to commonly held cylindrical objects (e.g., soda can, soup can). The object had a base mass of 60.0 g with a symmetrical distribution of mass along each axis of rotation. Two pegs extended orthogonally from the central cylinder in each direction, allowing for ring weights to be symmetrically added/removed (40 g and 120 g) for a manipulation of total object mass. The object was also equipped with a wrist strap to prevent accidental release of the object. (b) The experimental task. In this illustration, the participant is completing the task with the right UE (left UE is not depicted for clarity). Participants moved the held object to coordinate with the smaller moving cylinder (i.e., the target). The displacement of the virtual target and the length of the track tube were proportional to the length of each participant's UE so that shoulder flexion/extension did not exceed 30 degrees from the initial shoulder position. The target and track tube were positioned exactly one arm length in front of each participant. Participants were instructed to maintain full elbow extension throughout each trial. If a participant presented with biceps spasticity, the length of the track tube was adjusted based on the effective length of the UE (i.e., shortest distance from shoulder center of rotation to object center of mass; values reflected in Table 1). (c) Trajectory conditions. The target followed a predictable trajectory (i.e., a sine waveform with a frequency of 0.43 Hz) or an unpredictable trajectory (i.e., smoothed fractional Brownian motion with a Hurst exponent of 0.25; fBm). Different fBm trajectories were used for each trial (i.e., a new random signal). The set of target trajectories was the same for each participant. Y-axis units are in terms of object position along the track tube (i.e., 0 = center of track tube, ± 1 = upper and lower portions of track tube). Abbreviation a.u., arbitrary units.

(unaffected/dominant or affected/nondominant) was counterbalanced across participants in each group. Each trial lasted 20 s. To avoid fatigue, each participant rested for a self-selected period between trials. Participants received one practice trial prior to data collection.

Maximum pad-to-pad prehensile force was measured with a pinch gauge (B&L Engineering, Santa Ana, CA, USA) after the experiment. Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971).

### 2.3. Data processing & measures

LF was computed based on the object's vertical accelerations (derived from measured position, applying a 4th-order, low-pass, zero-lag Butterworth filter with a cut-off frequency of 6 Hz at each step of differentiation) through inverse dynamics calculations, taking into account object mass and gravitational force. GF was directly measured from the load cell and identically filtered.

Root mean square (RMS) deviation of observed object motions (zscore normalized) from actual target trajectories was used to determine tracking accuracy. Mean and standard deviation (SD) of GF and LF were calculated.

Cross-recurrence quantification analysis (CRQA) (Marwan and Kurths, 2002) was performed to assess GF-LF coupling. CRQA quantifies the number of shared locations (i.e., cross-recurrence) of two time series in a reconstructed phase space (Shockley, 2005). We tracked instances of cross-recurrence between centered- and unit-normalized GF and LF over the course of a trial, illustrated as dark points in cross-recurrence plots (CRPs) (Marwan and Kurths, 2002). We quantified cross-recurrence using two metrics that capture the pattern of GF-LF coupling: *Determinism* and *trapping time* (TT). Determinism is the percentage of points that fall on a diagonal line in a CRP; this occurs when the two signals exhibit covarying changes over time, and indicates the degree of continuous GF-LF coupling between the two signals (Webber and Zbilut, 2005). TT is the mean length of vertical lines in the CRP, reflecting the tendency of a signal to become "trapped" at one location while the other signal varies about that location (Coco and Dale, 2014). High TT indicates more intermittent GF-LF coupling—periods of non-responsiveness of one signal to the other interrupt periods of covariation between the two signals. CRQA parameters were determined for each trial using the routine of Coco and Dale (2014).

Sample entropy (SampEn) (Richman et al., 2004) was used to evaluate changes in GF and LF predictability. SampEn is the negative natural logarithm of the conditional probability that a data vector, having repeated itself within a tolerance $r$ (radius) for $m$ points, will also repeat itself for $m + 1$ points. SampEn parameters of template length, $m$, and radius, $r$ were estimated following Ramdani et al. (2009). More repetitive (i.e., predictable) signals exhibit lower SampEn (Yentes, 2016).

### 2.4. Statistical analysis

Data processing and statistical analyses were performed using custom MATLAB (R2019a, Mathworks, Natick, MA), R (v.3.5.1), and RStudio (RStudio, Inc., Boston, MA) scripts. All measures were log-transformed to meet analysis assumptions. Mixed-effects modeling was implemented with mass, trajectory, limb, group, and their interactions as fixed effects and participant as a random effect. A backward stepwise approach was used for model building. Models were trimmed by removing nonsignificant effects individually, progressing from higher- to lower-order interactions. At each step, we compared the deviance ($-2$ Log Likelihood; $-2$LL) between a larger model and a simpler nested model that excluded the predictor under analysis. The change in $-2$LL follows a chi-square distribution with degrees of freedom equal to the difference in the number of parameters between nested models, allowing for a test of statistical significance. The final model only included higher-order interactions that significantly improved model fit (and all component lower-order interactions and main effects). Simple-effects analyses and pairwise comparisons were performed to follow up on significant interactions. Degrees of freedom for pairwise comparisons were corrected using the Kenward-Roger method. Alpha was adjusted with the Tukey correction. Cohen's $d$ was calculated using a pooled SD.

## 3. Results

### 3.1. Manipulation check

#### 3.1.1. Tracking performance

In the final model, there was a main effect of trajectory, $t(356.7) = -23.99$, $p < .001$. There was also a significant trajectory × group interaction, $t(357.0) = -5.47$, $p < .001$. Follow-up pairwise comparisons revealed a significant difference between groups, but only in the sine condition where tracking performance was less accurate for children with CP than TD children, $t(24.5) = 3.67$, $p < .01$, 95% CI [0.01, 0.09], $d = 1.08$ (CP: $M = 0.15$, $SE = 0.01$; TD: $M = 0.10$, $SE = 0.01$). There was no difference in tracking performance between groups in the fBm condition, $t(25.1) = 0.80$, $p = .85$ (CP: $M = 0.27$, $SE = 0.01$; TD: $M = 0.26$, $SE = 0.01$). As expected, there was increased error in the fBm than sine condition, regardless of group, all $ps < 0.001$.

#### 3.1.2. LF magnitude

The final model showed significant main effects of mass, $t(361.4) = -5718.25$, $p < .001$, and trajectory, $t(361.3) = -21.00$, $p < .001$. There was also a significant mass × trajectory interaction, $t(361.7) = 7.02$, $p < .001$. Follow-up pairwise comparisons showed that LF was greater in the high-mass ($M = 1.78$ N, $SE = 1.0 \times 10^{-4}$) than the low-mass ($M = 1.19$ N, $SE = 1.0 \times 10^{-4}$) condition, regardless of trajectory, all $ps < 0.001$. LF was also significantly higher in the fBm ($M = 1.491$ N, $SE = 1.0 \times 10^{-4}$) than the sine ($M = 1.489$ N, $SE = 1.0 \times 10^{-4}$) condition, regardless of mass, all $ps < 0.001$. The mass × trajectory interaction seemed to stem from the fact that the change in LF associated with changes in mass was slightly higher for the fBm ($M = 0.5885$ N, $SE = 1.0 \times 10^{-4}$) than the sine condition ($M = 0.5875$ N, $SE = 1.0 \times 10^{-4}$). However, note that the quantitative difference in the effect of mass on LF between sine and fBm conditions was only 0.001 N—a value orders of magnitude lower than the overall effect of mass, indicating the primary role of gravitational (as opposed to inertial) forces in determining LF in this task. Thus, while the mass × trajectory interaction was statistically significant (likely driven by the very low between-subjects variability—SE values of 0.0001), it is unlikely that the differential effect of mass for the fBm trajectory condition produced a salient change for participants.

There was also a significant trajectory × group interaction, $t(362.2) = -2.79$, $p = .01$. For both groups, LF was lower in the sine than the fBm condition; this difference was greater in TD participants (CP: $M_{diff} = 0.0023$ N, $SE = 2.0 \times 10^{-4}$; TD: $M_{diff} = 0.0026$ N, $SE = 1.0 \times 10^{-4}$) (Fig. 2). The magnitude of the trajectory effect, though statistically significant, was again orders of magnitude lower than the effect of mass on LF and, thus, again not likely meaningful. Importantly, pairwise comparisons did not reveal any significant differences between groups. The differences previously noted in tracking performance in the sine condition did not appear to translate into meaningful differences in LF magnitude.

#### 3.1.3. Amount of LF variability

The final model for amount of LF variability (i.e., SD of LF) revealed significant main effects of mass, $t(366.1) = -14.31$, $p < .001$, and trajectory, $t(369.6) = -4.39$, $p < .001$. SD of LF increased as a function of mass (high: $M = 0.16$ N, $SE = 0.008$; low: $M = 0.11$ N, $SE = 0.008$). SD of LF was also greater in the fBm ($M = 0.14$ N,

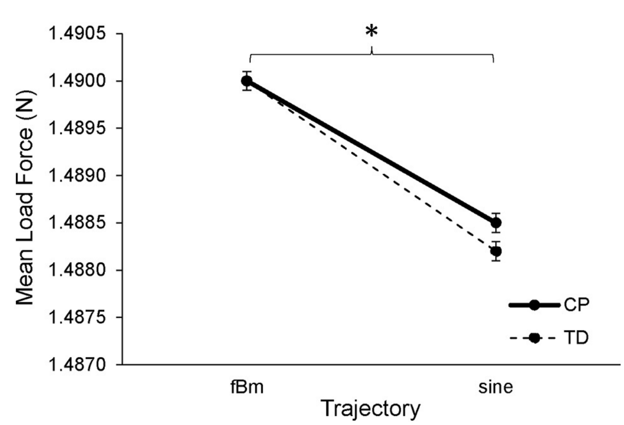


**Fig. 2.** Mean load force as a function of trajectory and group. Asterisk (*) indicates $p < .05$. Error bars represent the standard error of the mean.

*SE* = 0.008) than sine (*M* = 0.13 N, *SE* = 0.008) condition, regardless of mass, limb, or group. The manipulation of object mass modified task demands by increasing both LF magnitude and the amount of LF variability.

#### 3.1.4. LF predictability (SampEn)

The final model revealed significant main effects of trajectory, $t(357.0) = -15.74$, $p < .001$, and limb, $t(357.0) = 2.35$, $p = .02$, and a significant mass × trajectory interaction, $t(357.4) = 2.10$, $p = .04$. Follow-up pairwise comparisons revealed a significant difference between the high- and low-mass conditions only in the sine trajectory, regardless of group, $t(361.0) = -2.71$, $p = .04$, 95% CI [−0.03, −0.0008], $d = 0.31$. Overall, there was greater LF SampEn in the fBm (*M* = 0.45, *SE* = 0.007) than the sine (*M* = 0.36, *SE* = 0.007) condition with no differences between groups. The trajectory manipulation modified not only the amount but also the time-dependent structure of LF variability.

### 3.2. Grip control

#### 3.2.1. GF magnitude

The final model showed a significant main effect of mass on mean GF, $t(354.9) = -7.75$, $p < .001$. There was also a significant mass × limb × group interaction, $t(354.6) = -2.18$, $p = .03$, and a significant mass × trajectory × group interaction, $t(354.5) = 2.24$, $p = .03$. To follow-up on the mass × limb × group interaction, the model was fit separately for each limb. Results showed a significant mass × group interaction for mean GF, but only in the affected/nondominant limb, $t(156.3) = 2.67$, $p = .01$. Pairwise comparisons only revealed differences between groups in the low-mass condition, $t(24.2) = 2.93$, $p = .03$, $d = 1.09$, where children with CP showed higher levels of GF (Fig. 3). Pairwise comparisons also indicated that both groups demonstrated the expected increase in GF when mass was increased, all *ps* < 0.01. When children performed the task with the unaffected/dominant hand, there was only a main effect of mass, $t(181.3) = -9.31$, $p < .001$. As expected, GF was higher in the high-mass (*M* = 3.22 N, *SE* = 0.18) than the low-mass (*M* = 2.26 N, *SE* = 0.13) condition.

To follow up on the mass × trajectory × group interaction, the final model was fit for the sine and fBm conditions separately. Results showed a significant mass × group interaction for GF, but only for the sine condition, $t(166.6) = 3.55$, $p < .001$. GF increased significantly when mass increased in both groups, but more so for children with CP. When children performed the task in the fBm condition, there was only a main effect of mass, $t(171.7) = -7.33$, $p < .001$. As expected, GF was greater in the high-mass (*M* = 3.22 N, *SE* = 0.15) than the low-mass (*M* = 2.16 N, *SE* = 0.10) condition.

#### 3.2.2. Amount of GF variability

The final model for GF variability (i.e., SD of GF) showed a significant mass × trajectory × limb × group interaction, $t(348.1) = 2.28$, $p = .02$. To follow-up on the mass × trajectory × limb × group interaction, the model was fit separately for each limb. There were no significant interactions for the unaffected/dominant limb. However, the main effect of mass approached significance, $t(181.1) = -1.82$, $p = .07$, such that there was a slight increase in GF variability in the high-mass condition (*M* = 0.28 N, *SE* = 0.03) compared to the low-mass condition (*M* = 0.24 N, *SE* = 0.03).

For the affected/nondominant limb, there was a main effect of trajectory, $t(152.5) = 2.61$, $p < .01$, and a significant mass × group interaction, $t(153.2) = -2.35$, $p = .02$. While the mass × trajectory × group interaction only approached significance, $t(152.9) = 1.88$, $p = .06$, we followed up on this effect to better understand the four-way interaction. To that end, the model was fit separately for each group. Children with CP demonstrated a significant main effect of trajectory, $t(69.1) = 2.77$, $p < .01$, such that there was greater variability in the sine (*M* = 0.39 N, *SE* = 0.07) than the fBm (*M* = 0.29 N, *SE* = 0.05) condition, regardless of mass. This was in contrast to TD children who demonstrated a significant main effect of mass, $t(84.0) = -3.60$, $p < .001$, such that there was greater variability in the high-mass (*M* = 0.26 N, *SE* = 0.03) than the low-mass (*M* = 0.18 N, *SE* = 0.02) condition, regardless of trajectory.

#### 3.2.3. GF predictability (SampEn)

A significant main effect of mass, $t(349.2) = -2.39$, $p = .02$, was found along with a significant mass × trajectory × limb × group interaction, $t(348.7) = -2.20$, $p = .03$. To follow-up on this interaction, the model was fit separately for each limb. There were no significant main effects or interactions found in the unaffected/dominant limb. In the affected/nondominant limb, there was a significant main effect of mass, $t(159.6) = -4.46$, $p < .001$, and a significant mass × trajectory × group interaction, $t(159.0) = -3.58$, $p < .001$.

To follow-up on the mass × trajectory × group interaction, the model was fit separately for each mass condition. In the high-mass condition, there was a significant trajectory × group interaction, $t(73.7) = 2.36$, $p = .02$. Pairwise comparisons revealed no significant differences. The interaction appeared to arise from TD children demonstrating an increase in GF predictability in the sine condition, compared to children with CP demonstrating a decrease in GF predictability in the sine condition. In the low-mass condition, there were significant main effects of trajectory, $t(69.6) = 2.47$, $p = .02$, and group, $t(27.8) = 3.44$, $p = .001$. There was also a significant trajectory × group interaction, $t(70.0) = -2.65$, $p = .001$. Pairwise comparison revealed a significant difference between groups in the fBm condition, $t(32.4) = -3.26$, $p = .01$, 95% CI [−0.09, −0.001], $d = 1.11$ (Fig. 4).

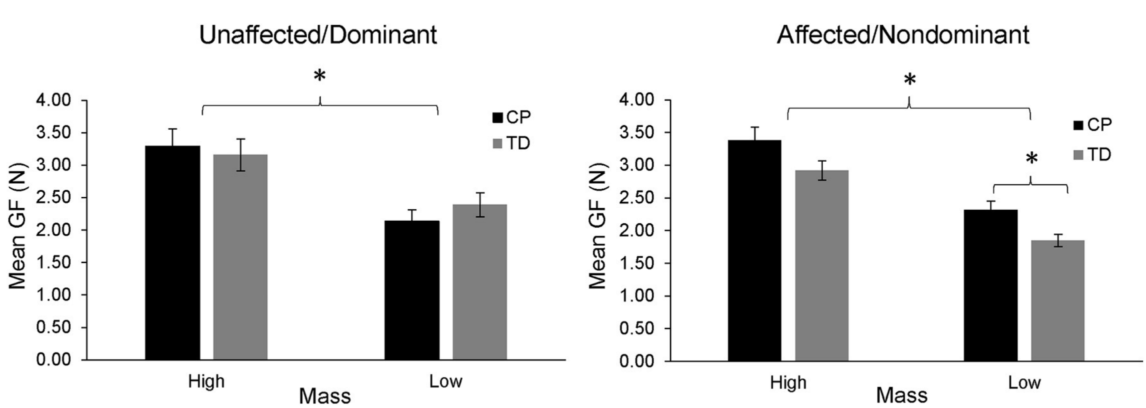


**Fig. 3.** Mean grip force (GF) as a function of mass and group, parsed by limb. Asterisks (*) indicate $p < .05$. Error bars represent the standard error of the mean.

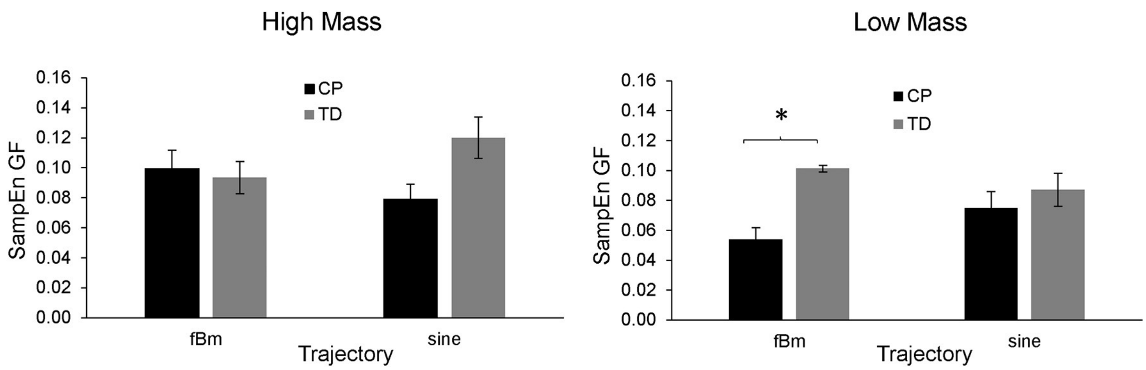


**Fig. 4.** SampEn of grip force (GF) as a function of trajectory and group in the affected/nondominant limb, parsed by mass. SampEn parameters of template length, *m*, and radius, *r*, were estimated from a random sample of participants and applied to all trials, $m = 1$, $r = 0.3$. SampEn was estimated using multiple sets of parameters to ensure that the pattern of results was consistent across parameter choices. Asterisk (*) indicates $p < .05$. Error bars represent the standard error of the mean.

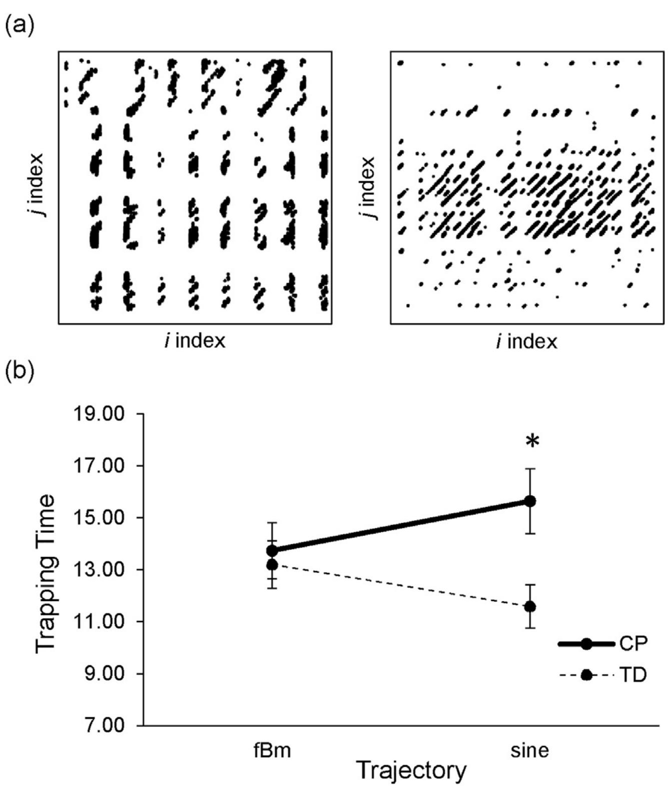


**Fig. 5.** (a) Example cross-recurrence plots (CRPs) of load force (LF) versus grip force (GF) for one participant with CP in different task conditions. Vertical line structure (i.e., intermittency) is observed in the unaffected limb, low-mass, sine condition (left), while more diagonal line structure (i.e., increased determinism/continuous coupling) is noted in the same participant in the unaffected limb, high-mass, and fBm condition (right). CRP axis labels indicate units of time (i.e., LF at time *i* and GF at time *j*), and dark points indicate that GF and LF were cross-recurrent at time [*i, j*]. CRQA parameters were determined for each individual trial. Delay values ranged from 6 to 25 samples ($M = 8.74$, $SD = 1.98$), and embedding dimension ranged from 3 to 8 ($M = 4.98$, $SD = 0.82$). Radius was adjusted per trial to achieve a fixed recurrence rate between 2.25 and 2.5% ($M = 2.38$, $SD = 0.07$). CRQA metrics were also estimated with a recurrence rate between 1.0 and 1.25% to ensure a consistent pattern of results. (b) Trapping time in the affected/nondominant limb, high-mass condition. A significant difference between groups occurred in the sine trajectory. Asterisk (*) indicates $p < .05$. Error bars represent the standard error of the mean.

### 3.3. GF-LF coupling

Fig. 5adepicts CRPs for one participant with CP. The CRQA metrics confirmed the visible changes in GF-LF coupling between intermittent (indicated by vertical line structure in the CRP, indexed by TT) and continuous GF-LF coupling (indicated by diagonal line structure in the CRP, indexed by determinism) as task demands changed.

#### 3.3.1. Trapping time

The final model revealed a significant mass × trajectory × limb × group interaction, $t(342.1) = 2.56$, $p = .01$. To follow up on that interaction, the model was fit separately for each limb. In the unaffected/dominant limb, there were no significant main effects or interactions. In the affected/nondominant limb, there was a significant main effect of mass, $t(154.4) = 2.64$, $p = .01$. There was also a significant mass × trajectory × group interaction, $t(155.3) = 2.12$, $p = .04$. To follow up on the significant mass × trajectory × group interaction in the nondominant limb, the model was subsequently fit separately for each mass condition. In the high-mass condition, there was a significant trajectory × group interaction, $t(70.6) = -2.07$, $p = .04$. Pairwise comparisons revealed a significant difference between groups in the sine condition, $t(50.0) = 2.83$, $p = .03$, 95% CI [0.52, 8.83], $d = 0.99$, such that children with CP demonstrated increased TT in the high-mass condition of the affected limb (Fig. 5b). There was no difference between groups in the fBm condition. In the low-mass condition of the affected/nondominant limb, there were no significant main effects or interactions. Accordingly, the mass × trajectory × limb × group interaction appeared to be driven by the difference between groups in the high-mass, sine condition of the affected/nondominant limb, indicating that children with CP demonstrated more intermittency in grasp in this task condition compared to TD peers.

#### 3.3.2. Determinism

The final model revealed a significant main effect of trajectory on determinism, $t(336.7) = -4.72$, $p < .001$, along with a significant trajectory × limb × group interaction, $t(337.1) = -2.61$, $p = .01$. The model was fit separately for each limb to follow-up on the trajectory × limb × group interaction. In the unaffected/dominant limb, there was a significant main effect of trajectory, $t(169.7) = -4.02$, $p < .001$, and a significant trajectory × group interaction, $t(169.5) = 2.39$, $p = .02$. Pairwise comparisons revealed significant differences between trajectories (fBm: $M = 0.992$, $SE = 5.88 \times 10^{-4}$; sine: $M = 0.988$, $SE = 5.62 \times 10^{-4}$), regardless of group (all $ps < 0.05$), while there were no differences between groups in either trajectory condition. The trajectory × group interaction is explained, however, by the greater decrease in determinism from fBm to sine found in children with CP ($M_{diff} = 0.0059$) compared to TD children ($M_{diff} = 0.0026$) in the unaffected/dominant limb. These results suggest that children with CP produced a greater change in continuous GF-LF coupling from the fBm to sine trajectories in the dominant limb. There was no significant trajectory × group interaction effect on determinism in the affected/nondominant limb. A significant effect of trajectory was found for both groups, $p < .01$, with higher determinism in the fBm ($M = 0.991$, $SE = 6.67 \times 10^{-4}$) than the sine ($M = 0.985$, $SE = 6.94 \times 10^{-4}$) condition in the affected/nondominant limb.

## 4. Discussion

This study aimed to determine whether differences in grip control between children with CP and their TD peers were modified by task demands, in particular by the amount and nature of LF variability related to UE kinematics during a target tracking task. The findings support our hypothesis: An attenuation of CP-related impairments was observed under task conditions which were previously shown to promote more continuous GF-LF coupling in TD adults (Grover et al., 2018, 2019a, 2019b, 2020).

Our results are partly consistent with findings of previous studies using predictable, sequential grip-lift-hold tasks in which children with CP demonstrated less responsive grip control and less efficient grasp compared to TD peers (Duff and Gordon, 2003; Eliasson et al., 1992; Gordon and Duff, 1999). In the more predictable sine trajectory conditions of the current study, children with CP demonstrated similar impairments: A less efficient grip control pattern (i.e., a greater change in mean GF for similar increases in LF) and reduced responsiveness of GF-LF coupling. However, these differences were not found in the unpredictable fBm trajectory condition. Thus, grip control in children with CP was more like grip control in TD children when task demands induced more unpredictable LF patterns. Such findings may inform therapeutic interventions targeting grip control in children with CP. Unpredictability introduced through UE movements may be one beneficial approach.

Both children with CP and their TD peers exhibited task-dependent changes between intermittent and continuous GF-LF coupling. Utilizing different modes of grip control as task demands change may be an important adaptive feature of the motor control system (Grover et al., 2018; Grover et al., 2019b), and this feature seems to be generally preserved in CP. "Drift-and-act" control (Milton, 2013) has been one proposed mechanism for the presence of intermittency in GF control in TD adults (Grover et al., 2019b). Under this control principle, active adjustments in GF occur only when task demands (e.g., fluctuations in LF) increase above a particular threshold. Subthreshold fluctuations are met with "drifting," that is—a cessation of active GF modulation while potentially exploiting intrinsic mechanical factors such as musculoskeletal viscoelastic properties (Loeb, 1995) to passively counteract LF fluctuations. Consistent with drift-and-act, children with CP and TD children demonstrated more continuously responsive patterns of GF (less intermittency) when LF variations were more unpredictable and, thus, at potentially greater risk of crossing the threshold for eliciting active control. As noted, the degree of intermittency was higher in general when LF variations were more predictable, but more so for children with CP. This result suggests that children with CP have a higher threshold for acting, which was crossed less frequently in the latter condition. One possible reason for this higher threshold is that the mechanical properties of muscles and tendons are altered (i.e., less compliant) in CP (Malaiya et al., 2007; Smith et al., 2011) and, thus, might allow for a greater range of fluctuations to be effectively counteracted passively without the need for active adjustments.

A higher threshold to "act" is also consistent with other motor impairments in CP: Stereotypy, resistance to change (Bar-Haim et al., 2008), and increased regularity (Donker et al., 2008). Accordingly, more unpredictability (compared to what is required in TD individuals) may be needed to overcome these intrinsic factors and allow children with CP to shift into a new motor pattern. Unpredictability has been found to weaken stereotypical movement patterns in CP, in turn introducing flexibility to the motor control system (Bar-Haim et al., 2008). Our findings support the potential benefit of unpredictability in weakening stereotypical motor patterns in CP.

Despite children with CP demonstrating more continuous GF-LF coupling in the fBm trajectory, similar to TD children, this condition was associated with lower GF SampEn in the affected/nondominant limb, low-mass condition. These results are consistent with a "change-in-regularity" approach (Vaillancourt and Newell, 2002), in which behavioral and physiological regularity increases in some situations and decreases in others, depending on the interaction between task- and individual-level constraints. Thus, even under conditions in which more continuous GF-LF coupling was observed, children with CP showed a difference in GF regularity compared to TD peers.

A relatively small sample of participants, although homogenous (in terms of hand function and grip maturity), was included. Thus, null findings should be interpreted with caution. However, the results are consistent in showing (at minimum) an attenuation of impairments under certain task conditions. The results may not be generalizable to individuals of MACS levels III-V. Future work with increased sample heterogeneity should be conducted to enhance generalizability. Our task paradigm only assessed grip control in the vertical plane. Functional tasks involve multiple planes of movement, and future work may investigate if our findings generalize to other planes.

## 5. Conclusions

Grip control impairments in children with CP were more manifest under more predictable task contexts—contexts dominant in the literature from which current therapeutic assessments and interventions are derived. Less predictable task demands attenuate impairments and could be leveraged in interventions designed to enhance GF-LF coordination in functional tasks.


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## Declaration of Competing Interest

The authors have no declarations of interest.


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