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Three-dimensional assessment of finger individuation reveals finger- and joint-specific selective motor control deficits in children with cerebral palsy

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Abstract

Background Children with cerebral palsy (CP) exhibit impaired selective motor control (SMC) that contributes to poor hand function, but current clinical assessments lack the sensitivity to detect finger- and joint-specific deficits to guide rehabilitation strategies. This study aimed to determine the internal consistency and validity of an objective, instrumented assessment of selective finger control (individuation) in children with CP, and to examine its relationship to clinical measures of upper limb function.

Methods A custom-designed device recorded three-dimensional isometric forces concurrently from all five fingertips to compute a composite metric of finger SMC (Individuation Index) for each tested finger and force direction. Group differences in individuation ability were quantified using linear mixed-effect models. Relationships between individuation and clinical assessments were assessed with Spearman correlation (r_s).

Results Twenty-eight children with CP and 18 typically developing control children were included. The non-preferred arm was tested in most children with CP ($n=16$), with the preferred arm tested in controls and the remaining CP cohort. Individuation Indexes demonstrated excellent internal consistency across groups (all $R \geq 0.97$). Children with CP exhibited lower individuation than controls in both the preferred (Cohen's d (d) $=0.73$) and non-preferred hands, with deficits in the non-preferred hand more pronounced during finger flexion ($d=1.48$), in the index finger ($d=1.52$), and in those exhibiting mirror movements ($d=0.56$). Exploratory analysis in children with CP tested bilaterally ($n=6$) revealed finger-specific differences, with lower individuation observed in the index finger of the non-preferred hand ($d=1.36$). In children with CP, higher Individuation Indexes for ab-/adduction forces in the preferred hand were related to better fine and gross manual ability ($r_s = 0.86$ and 0.76, respectively; both $p<0.007$). Individuation Indexes were not related to clinical scores in the non-preferred hand, nor in controls (all $p>0.05$).

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Conclusions This study provides a consistent, valid, and sensitive method to quantify finger SMC in children with CP, revealing finger-, force direction-, and hand-specific impairments that highlight aspects of dexterity not captured by clinical assessments. Quantifying finger individuation enables more precise characterization of hand dysfunction, advancing mechanistic understanding and targeted intervention design for children with CP.

Trial registration Data collected as part of a larger randomized controlled trial; https://clinicaltrials.gov/ct2/show/NCT03484078.

Keywords Cerebral palsy, Selective voluntary motor control, Fine motor, Hand function, Finger individuation, Dexterity, Perinatal stroke, Corticospinal tract, Mirror movements, 3D force analysis

Introduction

Cerebral palsy (CP), the most common motor disability in childhood [1, 2], is a descriptive term [3] for a group of postural-movement neurodevelopmental disorders resulting from non-progressive damage or malformation of the nervous system during early development, leading to significant activity limitations [4]. Objective quantification of impairments is essential to clinical decision-making and intervention planning in CP, prompting efforts to standardize clinical assessments and outcome measures [5–7]. Motor impairments in CP [8] are broadly categorized as positive signs of excess muscle activity (i.e., hypertonia, primarily spasticity) [9] and negative signs reflecting insufficient magnitude and/or control of muscle activity, including muscle weakness [10], dyscoordination, impaired postural control [11], and reduced selective motor control (SMC) [12]. Negative signs contribute more substantially to activity limitations [13] and are more responsive to rehabilitation [14]. However, they may share neurophysiological underpinnings with spasticity [15] and most clinical assessments lack the specificity and sensitivity needed to distinguish between positive and negative motor signs, and/or to detect subtle subclinical impairments that can impede intervention effectiveness in children with CP.

Among negative signs, reduced SMC has received increasing attention for its adverse impact on functional outcomes in children with CP [16, 17]. The NIH Pediatric Motor Disorders Taskforce defines reduced SMC as "the impaired ability to isolate the activation of muscles in a selected pattern in response to demands of a voluntary posture or movement" [12], which manifests clinically as obligatory patterns of muscle co-contraction, often called synergies [16] or enslaving [18, 19]. This clinical presentation is limb-specific in CP [20], and shares similar features as spasticity and weakness, necessitating thoughtful, directed assessment to guide intervention planning. Current assessments of SMC range from clinical observational tools that visually identify involuntary joint movement during isolated tasks [21, 22] to instrumented methods that quantify unintentional muscle activity [23, 24] or joint torques during isometric contractions [25, 26]. As walking 'correctly' without the obligatory synergistic mass patterns is a common rehabilitation goal for families and children with CP [27], greater emphasis has been placed on evaluating SMC in the lower extremities [28, 29], and its impact on walking ability [30, 31] and post-operative outcomes [32, 33]. Though impairments of manual dexterity are well documented in CP [34–38], the role of SMC in mediating these deficits has only recently been recognized [39, 40], spurring interest in SMC-directed interventions to improve hand function [41]. This limited focus in CP contrasts with research in adults post-stroke [42] that leverages finger individuation, the ability to isolate the intended finger(s) away from other fingers, to predict composite hand function and improve dexterity through targeted SMC interventions [43].

The increasing recognition of upper limb SMC impairment following early brain injury has led to the development of two novel clinical assessments for children with CP – the Test of Arm Selective Control [21] and the Selective Control of Upper Extremity Scale [44]. Greater emphasis has also been placed on SMC components within widely used and easily administered clinical assessments, such as the Dissociated Movement section of the Quality of Upper Extremity Skills Test [45] and the Fugl-Meyer assessment [46]. However, both CP-specific SMC assessments [21, 44] rely on subjective clinician ratings on an ordinal scale, which highlight general loss of function across larger proximal joints but lack the granularity to detect impairments at individual fingers and distal joint control that is critical for dexterous function. These tools typically collapse distinct components of finger control, such as force-direction and joint-specific force metrics, into a single composite score or rating (e.g., 'normal', 'impaired', or 'absent'), which risks oversimplification of motor deficits and overlooks finger- and joint-specific variability in SMC previously documented in adults with stroke [47, 48]. Additionally, the reliance on visual observation and inability to differentiate selective joint control from weakness reduces sensitivity to subtle changes in joint forces or muscle activation [23], and ordinal ratings further constrain responsiveness, which limits the utility of these tools to detect small but

clinically meaningful changes, or track intervention-induced SMC improvements.

A prominent aspect of upper limb SMC is finger individuation [49, 50], with independent finger movements deemed essential for dexterous hand function. Isolated finger movements are primarily mediated by corticospinal tract (CST)-driven regulation of motor unit recruitment. This regulation occurs via direct monosynaptic connections to spinal motor neurons (corticomotoneuronal system), and through indirect modulation of spinal interneuronal networks [51–53]. Damage to the CST during early development in CP [54, 55] disrupts these intricate control systems and contributes to upper limb dysfunction. Greater CST injury has been linked to more severe reaching deficits and impaired hand use in children with arterial perinatal stroke [56]. Notably, isolated CST damage produces severe and permanent deficits in dexterity, but more gross functions like power grip appear relatively spared [57], suggesting the biological systems supporting independent finger movements are distinct from those underlying strength [48, 58].

The strength-individuation dissociation necessitates distinct methodological approaches to quantify finger individuation separate from strength following brain injury. Previous studies either incorporated kinematic analyses of single or multidirectional finger motion via instrumented gloves [47, 59], or conducted kinetic analyses of whole-finger forces via robotic exoskeletons [60], manipulandums [61], or custom keyboards [48, 62]. Recent instrumented individuation assessments in individuals with CP [63, 64] reported heightened finger force interdependence (enslaving) in young adults with bilateral CP [63], and excessive force and movement enslaving in children with unilateral CP [64], highlighting the potential of quantitative methods to objectively capture SMC deficits across the lifespan and clinical spectrum of CP. However, these studies lacked the high-resolution kinematic and kinetic evaluations across all movement directions needed to accurately characterize individuation impairment patterns. Further, to date, no studies have conducted three-dimensional analyses of finger- and joint-specific forces in children with CP, and relationships of finger individuation metrics with hand function have not been described in this group.

To this end, the current study aimed to determine the internal consistency, sensitivity, and discriminative (known-groups) validity of a novel finger individuation assessment tool in children with CP using the Hand Articulation Neuro-training Device (HAND)—a novel device that concurrently measures three-dimensional isometric forces from all five fingertips during isolated finger force control [65]. For this study, we use sensitivity to describe how precisely our individuation metric can distinguish between individuals with different levels of finger SMC, rather than its ability to detect change over time [66]. We also aimed to assess the effects of finger tested, force direction, the presence of mirror movements, age, and sex on individuation ability. Relationships between individuation and clinical assessments of upper limb function were quantified in children with CP and typically developing control children. We hypothesized that our finger-individuation protocol would demonstrate good-to-excellent reliability, high sensitivity, and robust discriminative (known-groups) validity, evidenced by children with CP displaying lower individuation ability than similar-aged controls, with group differences varying across fingers and force directions tested. In line with prior studies in adults with stroke that reported weak [47] or no correlations between finger individuation and hand function [59], we expected limited associations between individuation and upper limb clinical scores in children with CP. We also included an exploratory analysis comparing finger individuation ability between the preferred and non-preferred hand in a subset of children with CP, and hypothesized lower individuation in the non-preferred hand.

Methods

Participants

Children with spastic CP recruited for a separate randomized controlled trial (NCT03484078) from the Children's Healthcare of Atlanta, local schools, pediatric rehabilitation centers, and the Cerebral Palsy Foundation were asked to participate in this study. Similar-aged typically developing children were recruited as controls (Con) using the same recruitment strategies and locations. Children with spastic CP who could walk independently, follow instructions, and complete experimental tasks were included. Exclusion criteria for children with CP included: [1] a prior long-bone fracture in both limbs [2], bisphosphonate medication [3], orthopedic surgery within the previous 6 months [4], abdominal baclofen pump usage, or [5] botulinum toxin treatment within the previous 12 months. Typically developing children with no history of neurologic or motor disorders, height and body mass between the 5th and 95th age- and sex-based percentiles were included as controls. Exclusion criteria for controls included: [1] history of chronic medication use known to impact the musculoskeletal system [2], a fracture in the lower extremities within the past year, or [3] sustained participation in high-level physical activity.

Functional classification and clinical assessments

Manual ability for children with CP was classified by participants' parents using the Manual Ability Classification System (MACS) [67]. Those at MACS level I could handle most objects easily and successfully, while those at MACS level II could handle most objects but with

somewhat reduced quality and/or speed of achievement. Gross motor function was assessed by a trained physical therapist using the Gross Motor Function Classification System (GMFCS) [68]. A GMFCS level I indicates independent ambulatory ability with some limitation in running or jumping, while a GMFCS level II indicates inability to run and jump with some limitation in walking long distances. The presence of spasticity, dystonia, or mixed tone (co-occurrence of spasticity with dystonia) was assessed using the Hypertonia Assessment Tool [69]. Mirror movements were visually assessed as present or absent during repeated fist opening-closing of one hand in isolation while keeping the non-tested hand as still as possible [22].

Experimental design and procedures

Participant setup

Participants were comfortably seated with the trunk supported at a height-adjustable table. The HAND was fixed to the table surface using Velcro straps, and the tested forearm was pronated and secured to the HAND with a modified forearm-wrist brace and Velcro straps that prevented wrist and forearm movement while allowing multidirectional finger movements [65, 70] (Fig. 1a; also see **Supplement 1**). Each fingertip was fitted with a soft silicone cup attached onto the HAND's mounting sticks, and finger positions were individually adjusted to a comfortable resting posture that elicited minimum forces (< 1 N, Fig. 1b). Cup material and dimensions (length, thickness) were customized to balance practical concerns (comfort, fingertip positioning within the cup) with the minimal sufficient elasticity to allow direction-specific isometric forces to be exerted at the fingertips across the age range of participants. The resting posture was maintained by fixing the knobs on the HAND, and the mounting angle and distance of the finger cups from the adjustment knobs were recorded. All children with CP attempted the protocol with the non-preferred hand. The preferred hand was tested instead in those who could not complete the task with the non-preferred hand. An additional six participants completed the task with both hands. As previous literature observed no differences in finger individuation between hands in typically developing children [64], the preferred hand was tested for all controls.

Finger individuation task

The finger individuation task (Fig. 1b, see video in **Supplement 2**) is a simplified version of that previously described [70]. Briefly, participants applied sustained, directional isometric forces with one fingertip (instructed finger) to exert real-time positional control of an onscreen cursor (white ball) by repeatedly moving it between a home position (gray sphere) and a wall (gray rectangle) in a virtual three-dimensional space. Only instructed fingertip forces produced cursor movement, and participants were instructed to keep the other fingers as still as possible. Summed forces from the non-instructed fingers were reflected by the height of a vertical red bar, which participants were instructed to minimize throughout the trial. Force direction was specified by the appearance of a virtual wall. Participants were asked to move the ball from the start position (central black sphere) towards the target wall and back to the sphere repeatedly within the 15-second trial duration. Real-time performance feedback was provided by the cursor's real-time position and an increase in brightness of the virtual wall as the cursor approached the target. Cursor movement in the virtual Cartesian space was mapped to the joint space [70] (Fig. 1c). For example, index finger force change along the x-axes corresponded to metacarpophalangeal (MCP) joint adduction (+ x) and abduction (-x), and that along the z-axes corresponded to MCP extension (+ z) and flexion (-z), while force changes along the y-axes corresponded to proximal interphalangeal joint extension (+ y) and flexion (-y). For the thumb, an additional preprocessing step was applied by rotating the data 90° within the Y-, and then Z-planes to reorient it onto the same space as the other fingers, ensuring consistent Cartesian–anatomical mapping. Notably, the mapping of force directions to finger joint-specific actions reflects the predominant, but not exclusive, joint motions in the tested posture, as the intricate biomechanical coupling of finger joints prevents exclusive mapping of kinetic outcomes to joint-specific movements [49]. One trial was conducted for each of the six directions for each tested finger (thumb, index, and ring finger, in pseudorandomized order), resulting in 18 trials per session. Breaks were provided between trials as needed, and verbal encouragement and positive reinforcement were provided to optimize participant engagement.

Force data processing

Data were processed using custom MATLAB (MathWorks, Natick, MA) programs. Force data were smoothed using a low-pass filter (2nd order, cutoff frequency = 5 Hz) and converted to Newtons. Force trajectories for each trial were computed as the deviation from the initial data sample and were further summed over the x-, y-, and z-directions. Trials (10.4%) in which the summed force did not exceed a minimum force threshold (0.02 N) were excluded.

As participants completed multiple movements towards the target position (Fig. 2a), often with varying force magnitudes, instructed finger peak and trough forces (magnitude, timing) were identified for each force trajectory. Finger individuation ability was assessed for each of the six instructed directions in the three

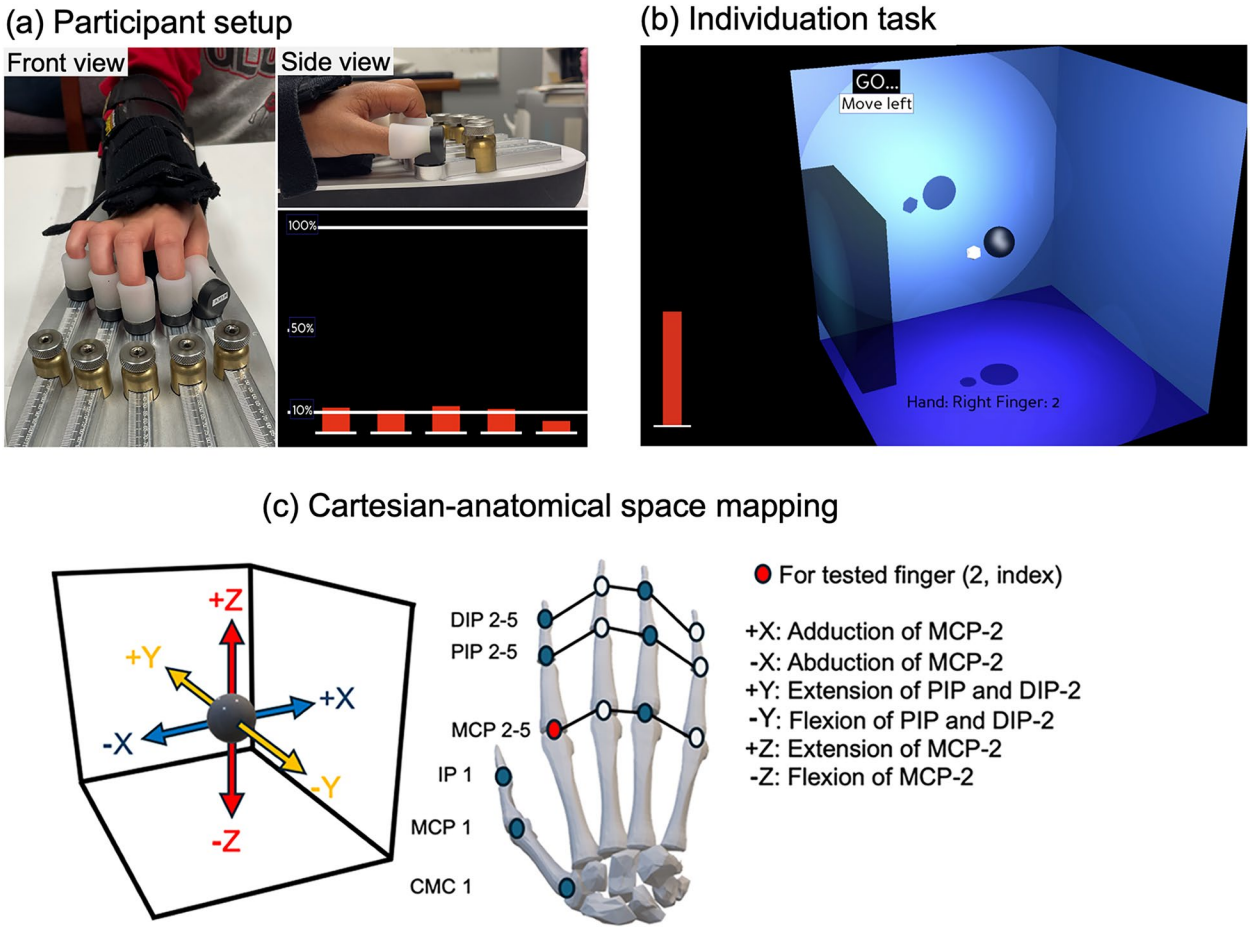

Fig. 1 Experimental setup and the three-dimensional finger individuation task. **a** Participant setup and positioning in the Hand Articulation Neurotraining Device (HAND). The tested hand was pronated and secured to the HAND with a customized wrist-forearm brace, which was fixed to a height-adjustable table. Each fingertip was placed in a flexible silicone finger cup, and finger positions were adjusted by manipulating each sensor arm angle and length (top view) till a comfortable resting posture was obtained (side view). **b** Final resting position was calibrated as the hand postur e that minimized overall fingertip forces to < 1 N (i.e., < 10% of the 10 N maximum, red bars on computer screen). This resting position was maintained across all trials. The tested hand, finger, and force direction were presented onscreen in a three-dimensional virtual workspace alongside a movement cue signaling trial onset. Participants used one (instructed) finger to control the position of an onscreen ball (white sphere) within a virtual workspace (blue box). The task required exerting sustained, direction-specific isometric forces at the instructed fingertip to move the ball from the start position (central gray sphere) toward a direction-specific target (gray wall) and back repeatedly within the 15-second trial. Real-time performance feedback was provided with the target wall turning lighter shades of blue with increasing proximity to the cursor. A red bar of variable height indicated the summed force from all uninstructed fingers, with participants instructed to minimize the bar height by restricting movement in these fingers. (**c**) Illustration of anatomical finger joint forces mapped to Cartesian coordinates in the virtual space. Each target direction corresponded to specific joint forces in the instructed finger. For example, the metacarpophalangeal (MCP) joint in the right-hand index finger corresponds to the x- and z-axes with adduction (+x), abduction (-x), extension (+z), and flexion (-z), while the proximal and distal interphalangeal joints (PIP and DIP, respectively) correspond to the y-axes with extension (+y) and flexion (-y). For the thumb, an additional preprocessing step was applied by rotating the data 90° within the Y, and then Z planes to reorient it onto the same space as the other fingers, ensuring consistent Cartesian–anatomical mapping

dimensions using an Individuation Index, as detailed in prior work by our group [48, 70]. Briefly, forces at the instructed finger were identified at each time-point when its force trajectory reached a peak or a trough during each trial (Fig. 2b). Forces from all the uninstructed fingers were computed as the mean deviation from baseline forces (*meanDevP*, Eq. 1) during intervals spanning consecutive peaks in the active force trajectory.

$$meanDevP = \frac{1}{T_k} \sum_{t_k=init}^{T_k} \sqrt{\sum_{j=uninstructed} (F_{tkj} - F_{jbaseline})^2} \quad (1)$$

Specifically, the root mean square of forces from all uninstructed fingers was computed at all time points from the preceding peak in the instructed finger active force (t_k) to the current trough in the same active force trajectory (T_k). The *meanDevP* was calculated for all intervals spanning each pair of successive peaks and troughs in the instructed finger summed force trajectory, for each trial. The Individuation Index was calculated using the slope

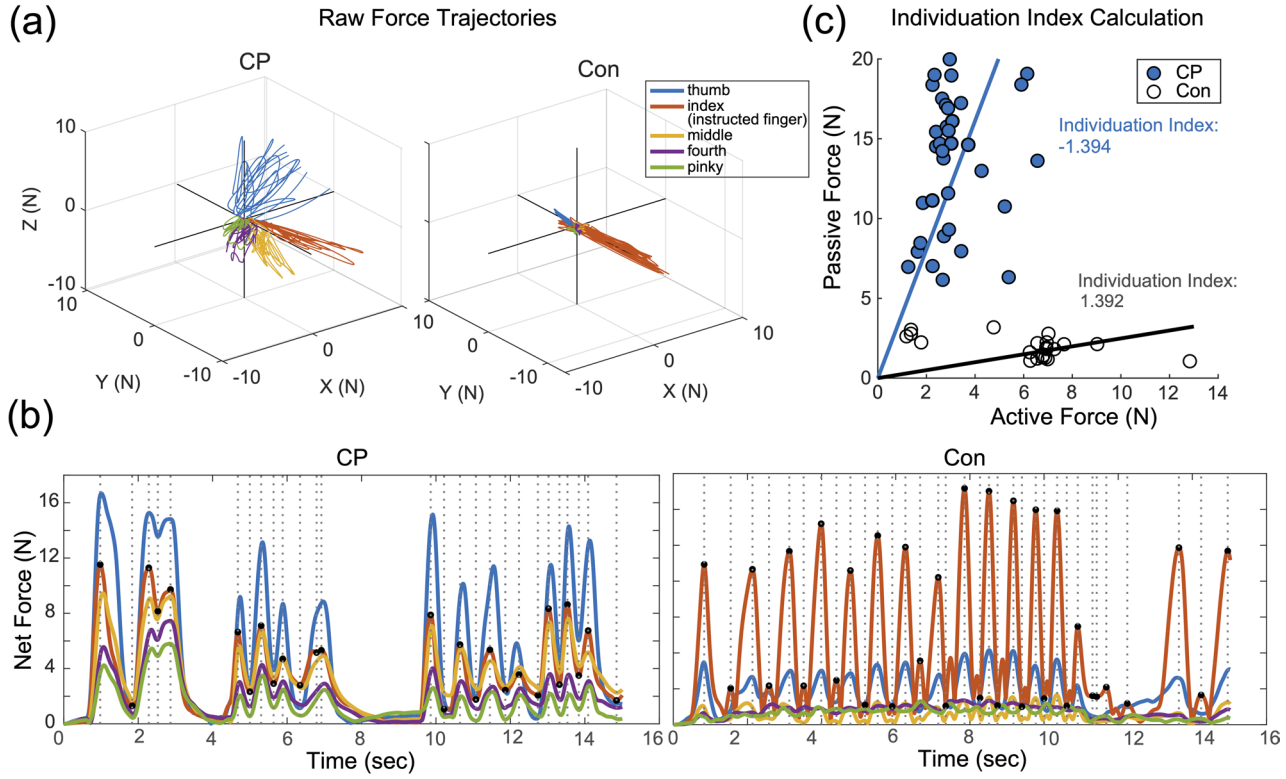

Fig. 2 Computation of the finger Individuation Index. **a** Sample raw forces (N) from a child with cerebral palsy (CP) and a typically developing control child (Con), both 11 years old, during a trial for index-finger flexion at the proximal interphalangeal joint (-Y direction). **b** Identification of force peaks and troughs in the instructed fingers and calculation of mean deviation from baseline force (*meanDevP*) in the non-instructed fingers across the 15-second trial duration. The summed force trajectories of the instructed finger (index finger, red line) are visualized alongside the summed force trajectories of the uninstructed fingers (other colored lines). Peaks and troughs in instructed finger forces were identified (black dots, dotted lines signifying time-points), and uninstructed finger forces during intervals between successive peaks and troughs were calculated as the root mean square (RMS) and summed across all uninstructed fingers (*meanDevP*). These force trajectories were computed using the raw forces from the same trials as shown in panel (a). **c** Illustration of Individuation Index derivation.A robust linear regression function was estimated for instructed finger forces against the *meanDevP* from the non-instructed finger forces, with the Individuation Index computed as the -log(slope) of the robust regression line

of a robust linear regression function ('*robustfit*' function, MATLAB) of *meanDevP* across all uninstructed fingers against forces at the instructed finger (Fig. 2c). The *robustfit* function uses an iteratively reweighted least squares approach to minimize the impact of outliers, with residuals Studentized to account for heterogeneous variances across levels of predictor variables. The Individuation Index was then normalized using log transformation and multiplied by -1 [Individuation Index= -log(slope)], so that more negative values (higher slopes) represent lower individuation ability. A single Individuation Index was calculated for each force direction (x-, y-, and z-directions) by each instructed finger.

Internal consistency of the computed Individuation Index was assessed for each group using the split-half reliability method [71]. For each trial, peaks and troughs data points were randomly split into two halves 10 times, and an Individuation Index was computed from each half. Correlations between the two halves were then computed. As there is increased variability when splitting data into halves due to the reduced number (half) of data points included for each computation [71, 72], in line with our previous work [48, 70], the Spearman-Brown correction was applied to improve reliability estimates using the formula $R = \frac{2r_p}{r_p+1}$, where r_p is the mean correlation coefficient across all 10 splits. Split-half reliability metrics indicated excellent internal consistency for Individuation Indexes in the non-preferred (R = 0.97) and preferred (R = 0.98) hands in CP, and in the control group (R = 0.98), in line with our previous work in adults with stroke [48, 70].

Clinical assessments of upper limb function

Standardized clinical assessments were used to evaluate manual ability and dexterity (video demonstrations in **Supplement 3**). The Purdue Pegboard Test (PPT) [73] measures unimanual dexterity through the number of standardized pegs a participant can sequentially place into a pegboard in 30 s [74]. A higher number of pegs placed indicates better fine manual ability [75]. The Box and Blocks Test (BBT) [76] measures gross unimanual

ability through the number of 1-inch blocks moved from one side of a partitioned box to the other in 60 s [77], with a higher number of blocks moved indicating better gross manual ability. The Functional Dexterity Test (FDT) [78] measures in-hand manipulation as a component of dexterous speed, and is computed as the number of pegs turned per second when a participant attempts to flip 16 pegs in a specified pattern [79]. Slower speeds indicates lower manual dexterity [80].

Statistical analyses

Group differences in physical characteristics were assessed using Independent t-tests for data that were normally distributed and with Mann-Whitney *U* tests for data that were not normally distributed, with chi-square or Fisher's exact tests used for categorical variables as appropriate. Linear mixed-effect model (LMM) analyses implemented in RStudio with the *lmerTest* package [81] were used to test differences in Individuation Indexes across conditions. Participant was included as a random factor to account for systematic variability introduced by subjects, while Group (CP vs. Con), Finger (thumb, index, and ring), Force Direction (flexion, extension, ab/adduction), Mirror Movement (present, absent), Age, and Sex were included as fixed factors. In a separate exploratory, repeated-measures analysis restricted to participants with CP who completed testing with both hands, Hand (preferred, non-preferred) was included as a fixed factor to examine within-subject differences in individuation ability. Significant effects were followed by post-hoc comparisons using the *emmeans* package [82] with alpha set at 0.05 and correction for multiple comparisons done via the Benjamini-Hochberg method [83]. Student's t-tests were used to compare clinical scores across groups. Spearman rank correlations (r_s) were used to assess relationships between Individuation Indexes and raw clinical scores in each arm in children with CP, and in the preferred arm in controls. Given prior evidence of force direction-specific associations in adults post-stroke [60], all correlational analyses were replicated using Individuation Indexes for each force direction, and age-corrected partial Spearman correlation was used to determine if relationships were driven by age effects. Magnitude of effects was quantified using Cohen's d (*d*), with cut-off values of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively [84].

Table 1 Participant characteristics of children with cerebral palsy (CP) and typically developing control children (Con)

	CP (*n* = 28)	Con (*n* = 18)	*d*	*p*
Age (years)	9.2 ± 1.9	9.0 ± 2.4	0.097	0.937
Sex (male/female)	18/10	13/5	–	0.749
Height (m)	1.34 ± 0.13	1.36 ± 0.15	0.169	0.437
Height (%)	47 ± 35	67 ± 22	0.634	0.110
Body mass (kg)	31.6 ± 7.6	32.2 ± 10.7	0.067	0.826
Body mass (%)	51 ± 33	60 ± 27	0.198	0.597
BMI	17.4 ± 3.0	16.9 ± 2.5	0.223	0.605
BMI (%)	54 ± 33	53 ± 27	0.021	0.955
Arm dominance (left/right)	15/13	0/18	–	< 0.001
CP diagnosis (unilateral/bilateral)	19/9	–	–	–
GMFCS level (I/II)	25/3	–	–	–
MACS level (I/II)	3/25	–	–	–
Mirror movement (present/absent)	14/14	–	–	–
Tested hand for individuation task (preferred only/non-preferred only/both hands)	6/16/6	18/0/0	–	–
Hypertonia Assessment Tool tested arm	20[a]/6[b]/4[c]/4[d]	–	–	–

Data are presented as mean ± SD. BMI, Body mass index; GMFCS, Gross Motor Function Classification System; MACS, Manual Ability Classification System; % for height, body mass, and BMI reflect percentiles relative to age- and sex-based norms. Muscle tone abnormality indicated by Hypertonia Assessment Tool rating as [a]normal tone, [b]spasticity, [c]dystonia, [d]mixed tone (both spasticity and dystonia present)

Results

Twenty-eight children with CP ($n_{\text{non–preferred arm only}}$ = 16, $n_{\text{preferred arm only}}$ = 6, $n_{\text{both arms}}$ = 6) and 18 typically developing control children (all preferred arm) aged 5 to 12 years participated in the study (Table 1). The only group difference was the greater number of children with CP who displayed left hand dominance ($p < 0.001$)

Individuation deficits in the non-preferred hand of CP vary by finger, force direction, and presence of mirror movements

We used LMMs with Participant as a random effect and Group, Force Direction, Finger, Mirror Movements, Age, and Sex included as fixed effects to evaluate differences in finger individuation between the CP non-preferred hand and the control preferred hand (Fig. 3a, **Supplement 4** - Table S4A). A Group × Force Direction interaction was observed after controlling for Finger ($p < 0.001$), with children with CP displaying lower Individuation Indexes than controls in all directions. Group differences were the greatest in flexion ($d = 1.48$, $p < 0.001$) followed by extension ($d = 1.09$, $p < 0.001$) and ab-/adduction ($d = 0.68$, $p = 0.001$). Both groups exhibited higher Individuation Indexes in flexion compared to extension (d_{CP} = 0.30, $p = 0.047$; d_{Con} = 0.68, $p < 0.001$) and ab-/adduction (d_{CP} = 0.34, $p = 0.017$; d_{Con} = 1.13, $p < 0.001$). However, differences in individuation between extension and ab-/adduction were observed in controls (d_{Con} = 0.45, $p = 0.001$), but not in children with CP (d_{CP} = 0.04, $p = 0.780$).

After controlling for Force Direction, a Group × Finger interaction ($p < 0.001$) revealed lower Individuation Indexes in children with CP compared to controls across

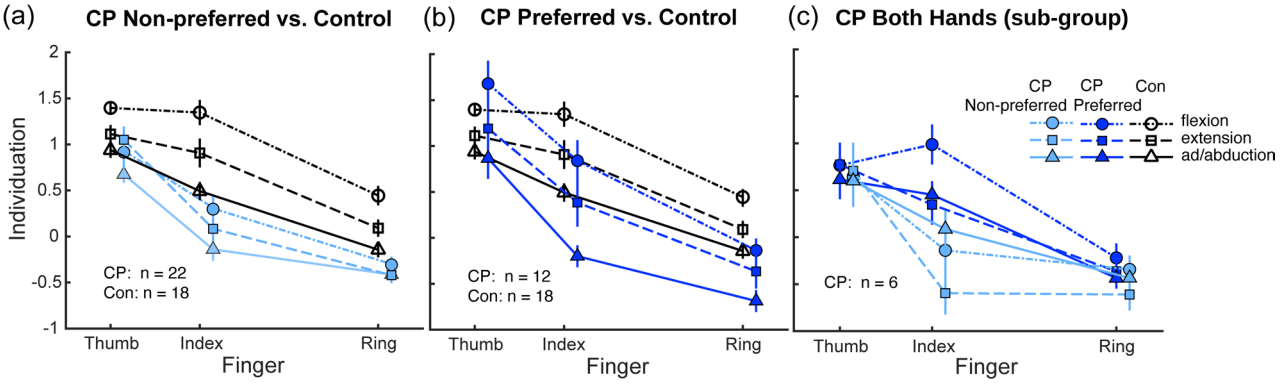

Fig. 3 Finger Individuation Indexes across force directions (flexion, extension, ab-/adduction) and fingers (thumb, index, ring) in each hand in children with cerebral palsy (CP) and in the preferred hand in typically developing control children (Con). (**a**) Comparison of individuation indexes between the non-preferred hand in children with CP versus controls. (**b**) Comparison of individuation indexes between the preferred hand in children with CP versus controls. (**c**) Comparison of individuation indexes between the preferred and non-preferred hands in a sub-group of children with CP who had both hands tested. Higher individuation index values reflect greater individuation ability, while negative values indicate reduced individuation ability

all tested fingers. Group differences were the greatest for the index finger ($d = 1.52$, $p < 0.001$), followed by the ring finger ($d = 0.90$, $p < 0.001$) and thumb ($d = 0.58$, $p = 0.003$). Within both groups, individuation was higher in the thumb compared to the index (d_{CP} = 1.31, $p < 0.001$; d_{Con} = 0.37, $p = 0.010$) and ring finger (d_{CP} = 1.92, d_{Con} = 1.67; both $p < 0.001$). Index finger individuation was also higher than the ring finger in each group (d_{CP} = 1.67, d_{Con} = 1.29; both $p < 0.001$).

A main effect of Mirror Movements was also observed ($p = 0.003$). Children with CP who exhibited mirror movements also demonstrated lower individuation than those without mirror movements ($d = 0.56$, $p = 0.004$). While both groups displayed lower individuation than controls, the magnitude of group differences was nearly twice in those with mirror movements ($d_{MirrorMovementPresent}$ = 1.19, $d_{MirrorMovementAbsent}$ = 0.63, both $p < 0.001$). No interactions were observed for Sex or Age (all $p > 0.05$). However, a main effect of Age ($p = 0.016$) suggested age-related improvements in finger individuation, with 12-year-olds displaying better individuation ability than 5-year-olds across the combined cohort ($d = 0.56$, $p = 0.020$).

Individuation deficits in the preferred hand in CP are consistent across fingers and force directions

Separate LMMs with Participant as a random factor and fixed effects for Group, Force Direction, Finger, Mirror Movements, Age, and Sex were used to assess patterns of finger individuation in the preferred hand of children with CP and controls (**Supplement 4** - Table S4B). Though no Group × Finger or Group × Force Direction interactions were observed (both $p > 0.05$; Fig. 3b), an LMM combining the 3 factors revealed significant main effects for each factor. Specifically, a main effect of Group ($p = 0.001$) was observed, with children with CP demonstrating lower overall finger individuation than controls ($d = 0.73$, $p = 0.001$). A main effect of Force Direction was also observed ($p < 0.001$), with individuation in the combined cohort higher during flexion compared to extension and ab-/adduction movements ($d = 0.67$ and 1.05, respectively, both $p < 0.001$), and higher during extension than ab-/adduction movements ($d = 0.39$, $p = 0.001$). Further, a main effect of Finger was also observed, with higher individuation in the thumb compared to the index and ring fingers in the combined cohort ($d = 0.53$ and 1.90, respectively; both $p < 0.001$). Individuation in the index finger was also higher compared to the ring finger ($d = 1.90$, $p < 0.001$).

While Group × Age and Group × Sex interactions were not observed (both $p > 0.05$), a significant main effect of Age ($p = 0.003$) revealed better finger individuation with increasing age in the combined cohort, with the oldest children at the age of 12 years displaying higher Individuation Indexes than the youngest participants at the age of 5 years ($d = 0.66$, $p = 0.004$). There was no effect of Mirror Movements on finger individuation ($p = 0.212$) in the preferred hand of children with CP.

Preliminary evidence suggests hand differences in individuation ability in CP are finger-specific

Exploratory within-subject analyses were conducted using separate LMMs in a small subset of participants with CP ($n = 6$) who completed bilateral testing (Fig. 3c, **Supplement 4** - Table S4C). Models included Hand, Finger, and Force Direction as fixed effects, with Participant as a random factor. A Hand × Finger interaction was observed after controlling for Force Direction ($p = 0.001$). Individuation was higher in the preferred hand compared to the non-preferred hand for the index finger ($d = 1.36$, $p < 0.001$), while no differences were observed between hands for the thumb or ring finger ($d = 0.15$ and 0.22, respectively; both $p > 0.05$).

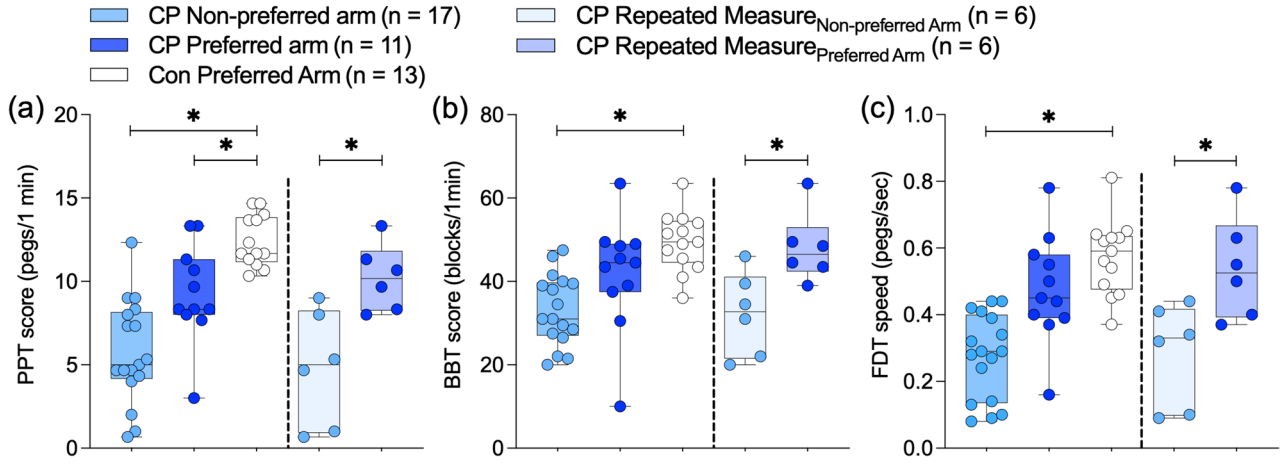

Fig. 4 Clinical assessment scores for (**a**) fine manual ability (Purdue Pegboard Test, PPT), (**b**) gross manual ability (Box and Blocks Test, BBT), and (**c**) in-hand manipulation (Functional Dexterity Test, FDT) in the preferred and non-preferred hand of children with cerebral palsy (CP) and typically developing control children (Con). A subset of children with CP ($n=6$) completed clinical assessments with both hands. *Statistically significant difference ($p<0.05$)

Table 2 Spearman rank correlation coefficients between finger Individuation Indexes for each force direction and clinical assessment outcomes in children with cerebral palsy (CP) and typically developing control children (Con)

	Mean Individuation Index			
	Overall	**Flexion**	**Extension**	**Ab-/Adduction**
Con Preferred arm ($n=13$)				
FDT score	$r_s=0.44$; $p=0.133$	$r_s=0.24$; $p=0.426$	$r_s=0.16$; $p=0.603$	**$r_s=0.62$;$p=0.025$**
BBT score	$r_s=0.22$; $p=0.476$	$r_s=0.12$; $p=0.694$	$r_s=0.01$; $p=0.979$	$r_s=0.50$; $p=0.083$
PPT score	$r_s=-0.05$; $p=0.864$	$r_s=0.06$; $p=0.843$	$r_s=-0.50$; $p=0.081$	$r_s=0.27$; $p=0.380$
CP Non-preferred arm ($n=17$)				
FDT score	$r_s=0.02$; $p=0.948$	$r_s=0.15$; $p=0.573$	$r_s=-0.13$; $p=0.613$	$r_s=0.16$; $p=0.548$
BBT score	$r_s=-0.03$; $p=0.926$	$r_s=-0.03$; $p=0.918$	$r_s=-0.13$; $p=0.619$	$r_s=0.03$; $p=0.922$
PPT score	$r_s=-0.04$; $p=0.885$	$r_s=0.04$; $p=0.885$	$r_s=0.02$; $p=0.929$	$r_s=-0.04$; $p=0.874$
CP Preferred arm ($n=11$)				
FDT score	**$r_s=0.62$;$p=0.043$***	$r_s=0.36$; $p=0.272$	$r_s=0.53$; $p=0.096$	$r_s=0.57$; $p=0.066$
BBT score	**$r_s=0.75$;$p=0.008$†**	$r_s=0.49$; $p=0.125$	$r_s=0.42$; $p=0.201$	**$r_s=0.76$;$p=0.007$†**
PPT score	**$r_s=0.64$;$p=0.033$**	$r_s=0.47$; $p=0.141$	$r_s=0.53$; $p=0.094$	**$r_s=0.86$;$p<0.001$†**

Statistically significant relationships are highlighted in bold

*Not statistically significant after multiple comparison correction

†Statistically significant after correcting for age with partial correlation analyses

Preferred hand finger individuation ability is linked to clinical scores in CP

Among participants who completed the finger individuation task, 22 children with CP ($n_{\text{Preferred arm}}$ = 11, $n_{\text{Non-preferred arm}}$ = 17; each including $n_{\text{Both arms}}$ = 6) and 13 typically developing control children completed the three clinical tests (Fig. 4a-c; Table 2). Children with CP exhibited worse performance on all clinical assessments with their non-preferred arm compared to the preferred arm in controls (d_{FDT} = 2.62, d_{BBT} = 2.21, d_{PPT} = 2.71; all $p<0.001$, Fig. 4a). Children with CP also displayed impaired fine manual ability with the preferred arm, with fewer pegs inserted on the PPT compared to controls ($d=1.38$, $p=0.003$; Fig. 4a). While not statistically significant, similar trends were also observed for preferred arm gross manual ability, with generally fewer blocks moved on the BBT ($d=0.72$, $p=0.092$; Fig. 4b) in CP than controls, and similarly impaired in-hand manipulation, observed as slower speeds on the FDT ($d=0.70$, $p=0.102$; Fig. 4c) in CP than controls. Exploratory within-group analyses of the six children with CP who completed clinical tests with both arms revealed worse upper limb function in the non-preferred arm compared to the preferred arm (Fig. 4a-c), with fewer pegs inserted on the PPT ($d=1.98$, $p=0.040$; Fig. 4a), fewer blocks moved on the BBT ($d=1.70$, $p=0.007$; Fig. 4b), and slower in-hand peg manipulation on the FDT ($d=1.67$, $p=0.036$; Fig. 4c).

Spearman rank correlational analyses (Table 2) between overall finger individuation ability and clinical assessment scores revealed significant positive associations in the preferred hand in children with CP. Higher overall Individuation Index in the preferred hand was related to greater fine and gross manual ability and faster in-hand manipulation (r_s range = 0.62 to 0.75; all $p<0.05$), with a statistically significant association observed for gross manual ability (i.e., BBT scores) even after controlling for age. To better understand the directional specificity of these associations, we performed exploratory analyses across force direction–specific Individuation Indexes. We observed strong positive relationships between finger individuation in the ab-/adduction direction and manual

ability scores in the preferred hand of children with CP. These associations remained statistically significant for both gross (BBT) and fine (PPT) manual ability after controlling for age (r_s = 0.76 and 0.86, respectively; both $p < 0.007$). In the preferred hand of controls, higher Individuation Index in the ab-/adduction direction was linked to better in-hand manipulation (FDT; r_s = 0.62, $p = 0.025$), though the relationship was not statistically significant after controlling for age ($p = 0.060$). Finger individuation was not significantly related to clinical test scores in the non-preferred arm of children with CP (all $p > 0.50$).

Discussion

This study investigated the reliability and sensitivity of an assessment tool for finger individuation in children with CP using the HAND, a novel device that captures simultaneous three-dimensional isometric force measurements from all fingertips. Our observations support its utility as a reliable, valid, and sensitive tool for assessing selective finger control in children with early brain injuries. Children with CP exhibited bilateral finger individuation impairments, with patterns of deficits appearing hand-specific. The non-preferred hand in CP demonstrated widespread deficits that varied by finger and force direction, and were linked to the presence of mirror movements. The index and ring fingers were more impaired in individuation ability, and flexion movements were most prominently impaired. Conversely, individuation deficits in the preferred hand in CP did not differ by finger tested, force direction, or the presence of mirror movements. Age-related improvements in individuation ability were similar across groups. Subgroup analyses comparing finger individuation across the two hands in children with CP revealed lower individuation specifically in the index finger of the more impaired hand, after controlling for force direction, reflecting findings from clinical assessments and reinforcing the discriminative capacity of our novel individuation paradigm. In children with CP, greater finger individuation in the preferred hand was associated with better fine and gross manual ability after controlling for age, with relationships most prominent for ab-/adduction forces, indicating direction-specific contributions of selective motor control to functional hand performance. The lack of significant associations in the non-preferred hand likely suggests that clinical tests and individuation-based tasks probe distinct aspects of motor control (i.e., multi-finger coordination versus joint-level selective control), and are consistent with prior work in adults with stroke [47, 59, 85]. Together, these results extend prior work by offering an objective and fine-grained metric of upper limb SMC that highlights the HAND's potential as a sensitive tool for assessment and individualized rehabilitation planning in CP.

Finger- and movement-specific deficits of individuation vary by tested hand in CP

Variable patterns of individuation deficits were observed across fingers and force directions in the non-preferred hand in children with CP, with the index and ring fingers showing prominent deficits bilaterally compared to relatively preserved individuation in the thumb, specifically within the preferred hand. These observations generally align with those reported in older adults with stroke [47, 59, 70, 85]. Our team [70] previously demonstrated finger- and force-direction specific patterns of impairment in individuation in adults post-stroke, with thumb flexion emerging as the sole direction of preserved function among those with greater upper limb impairment. Lang and Schieber [47] also reported bilateral sparing of thumb individuation in adults with pure motor hemiplegia, though impairments in index finger individuation were minor compared to the prominent deficits observed in children with CP in this study. In contrast, individuation deficits were uniformly observed across all five fingers in patients with subcortical lacunar stroke exhibiting more impaired hand function [59], with higher likelihood of CST damage in this group posited to contribute to their greater individuation impairments. These discrepant findings may be explained by developmental differences in individuation [86] and enhanced neuroplasticity after early brain injury [87, 88]. Additional contributors include methodological differences across studies, with the multidimensional HAND protocol assessing joint forces (i.e., kinetics) across 6 directions compared to the unidirectional flexion-extension kinematic protocol used in other studies [47, 59].

Individuation in the non-preferred hand in CP was more impaired during flexion than extension or ab-/adduction. We [70] previously reported individuation in the paretic hand of older adults with chronic stroke was least impaired during flexion movements. Neurophysiological differences between neurodevelopmental and adult-onset brain injury may underlie these discrepant findings. Adult-onset stroke is commonly associated with weakness and selective motor control impairments affecting the extensor muscles more than flexor muscles that are coupled with a bias toward co-contraction of these muscles in a stereotypical flexor synergy pattern [89, 90]. The flexor synergy commonly described in adult-onset stroke [90] is hypothesized to be driven by compensatory recruitment of the rubrospinal [16] and/or cortico-reticulospinal pathways [91] due to the loss of CST input following neural injury [92]. In contrast to direct CST inputs to distal extensors and hand intrinsics that support fractionated movements [51], the cortico-reticulospinal tracts supply multiple segments of the spinal cord [52], diffusely innervating multiple proximal arm muscles and distal flexor muscles. Given

these neurobiological characteristics, compensation by extra-pyramidal motor systems such as the reticulospinal and rubrospinal tracts after CST damage may result in a stronger flexor synergy but poorer selective control in the flexion direction. However, flexor synergy is expressed minimally in the upper limb of children with CP [20], and differences in synergy patterns are dependent on the timing of early brain injury [25]. Children with CP arising from post-natal lesions exhibited flexor synergies and minimal wrist-finger extensor activity, similar to the reticulospinal tract-driven patterns displayed by individuals with adult-onset stroke. Conversely, prenatal lesions commonly involve white matter damage (e.g., periventricular leukomalacia), with loss of contralateral corticospinal fibers compensated by preserved ipsilateral CST projections, with preserved finger and wrist extension capabilities [25].

Further, Xu and colleagues [70] did not find differences in individuation between the non-paretic hand in individuals with stroke and the dominant hand of young neurotypical controls, contrasting with this study's observations of significant differences between preferred hand individuation in children with CP compared to both controls and to their non-preferred hand. However, prior research in children with unilateral CP [64] reported finger individuation deficits in their preferred hand compared to controls. Interestingly, finger individuation metrics did not differ across hands in adults with spastic diplegic CP [63], though individuation was lower than controls for both the preferred (effect size $\eta_p^2 = 0.62$) and the non-preferred hand ($\eta_p^2 = 0.35$). These contrasting observations underscore developmental differences in dexterous impairment across the lifespan in individuals with CP [93], and highlight distinct recovery mechanisms in adult- versus childhood-onset brain injury due to enhanced developmental neuroplasticity [94] that warrants further investigation.

Individuation deficits in the non-preferred hand are linked to mirror movements in CP

In the present study, children with CP who displayed mirror movements had lower individuation in the non-preferred hand compared to those without mirror movements. To our knowledge, this is the first study to quantitatively link mirror movement expression to finger individuation deficits in children with CP. The etiological origins of these involuntary, obligatory movements differ by timing of brain injury, likely arising from preserved ipsilateral CST projections [95] and reduced interhemispheric inhibition [96] when competitive pruning signals from the lesioned hemisphere are suppressed following early brain injury [94, 97], or from upregulation of subcortical reticulospinal tracts following adult-onset stroke [98]. While these movements commonly recede in typically developing children with callosal pathway maturation and interhemispheric inhibitory control [99], persistent mirror movements beyond early childhood are commonly reported in individuals with CP, which can adversely impact both unimanual dexterous function and bimanual coordination [39] though beneficial impacts on the former have also been reported [100]. Our novel observation of the association between impaired individuation and mirror movements extends prior work by demonstrating that mirror movements are both potential markers of atypical CST [94, 97] or subcortical wiring [98], and are linked to poor selective finger control in children with spastic CP. However, further investigation is warranted to determine the presence and directionality of causal links between these constructs. Despite their potential shared neurophysiological underpinnings (e.g., persistent ipsilateral CST wiring, reduced interhemispheric inhibition, influence of brain injury timing), the potential interaction of selective finger control and mirror movement severity on mediating dexterous hand function requires further, focused exploration.

Finger individuation in the preferred hand is linked to clinical test performance in CP

We also examined how finger individuation relates to performance on clinical assessments of hand function. In children with CP, higher individuation in the preferred hand was associated with better fine (PPT) and gross (BBT) manual ability and faster in-hand manipulation (FDT), with relationships appearing strongest for ab-/adduction force directions. No relationships were observed in the non-preferred hand, and relationships in controls were weak and age-dependent.

Positive associations in the preferred hand of children with CP suggests that the Individuation Index captures joint-level selective control (e.g., interossei-mediated ab-/adduction at the metacarpophalangeal joints) that supports task performance in the relatively less impaired hand. Notably, better ab-/adduction control may enable or support compensatory grasp patterns (e.g., lateral pinch) that facilitate dexterous control despite corticospinal injury, consistent with the compensatory/adaptive movement strategies exhibited by children with CP when completing the clinical assessments in this study. The sole study to evaluate finger individuation and clinical hand function in children with CP [64] reported moderate positive associations between individuation and hand function, though analyses were exploratory and limited to small samples ($n_{CP} = 4$, $n_{Controls} = 10$), and used force data pooled across groups and both hands. However, emerging evidence in adults post-stroke suggests the strength of these relationships may depend on movement direction [60], necessitating direction-specific individuation assessment to disentangle the contributions of

distinct motor control components to functional hand performance following brain injury [48].

The absence of significant associations in the non-preferred hand in children with CP aligns with prior work in adults post-stroke that reported non-significant [59] or small-to-moderate [47, 85] associations between finger individuation and clinical tests of arm-hand function. These observations suggest that clinical assessments interrogate broader multi-finger coordination (e.g., tripod pinch, precision grasp), speed, and object manipulation, in contrast to the fine-grained, multidirectional joint-level selective finger control quantified by individuation assessments. Clinical test scores for the more affected hand likely reflect the composite influences of weakness, dyscoordination, sensory-perceptual deficits, and mirror movements, which may mask the relative contribution of selective finger control. Conversely, in typically developing children, this dissociation may reflect ceiling effects of clinical assessments.

Strengths and future directions

This novel work presents an important step in cross-validating an established instrumented methodology previously used for assessing selective finger control in adults post-stroke [47, 48, 50, 51, 70] within children with CP, a population for whom no gold-standard or objective benchmark for finger individuation currently exists. A key strength of this study is the use of a novel device capable of capturing finger- and direction-specific finger forces across three-dimensions and over multiple movement planes, allowing the quantification of subtle, distal joint-specific motor deficits likely undetected by conventional clinical evaluations. Despite evidence of disproportional involvement of distal joints [101, 102], current SMC assessments in CP [21, 44, 103] rarely probe joint- and movement-specific impairments in the hand, limiting their ability to guide targeted interventions. Force-derived Individuation Indexes from the HAND more sensitively capture selective finger control deficits in children with CP than kinematic-based motor control metrics [64], with lower values reflecting increased coactivation in adjacent fingers. These impairments may manifest clinically as difficulty pressing a single key, clumsy handling of small objects, or slower and less efficient manual performance during dexterous tasks, such as typing, buttoning, using a keyboard, or interacting with touchscreen digital devices and keypads. The high reliability and sensitivity of the HAND-derived Individuation Index, coupled with force direction- and hand-specific relationships with clinical hand function, both complement and enhance the precision of clinical assessments, and provide mechanistic insights to guide the development of targeted therapies to improve hand use in children with neurological damage.

This study opens several avenues for future research. Longitudinal studies are needed to characterize developmental trajectories of finger individuation in both typically developing children and those with CP. Co-occurring sensory-perceptual deficits and weakness may influence individuation outcomes [104], which merit integrated assessment in future investigations. Our previous work in adults with stroke [48] demonstrated that individuation has been linked to strength recovery in a threshold-dependent manner, where individuation and strength were dissociated once strength reached moderate levels (~ 60%) of recovery. However, no comparable insight exists for children with early brain injuries. Examining strength and individuation and their interaction [60] may offer new insights into functional motor recovery in individuals with CP.

Limitations

The modest sample size, though significantly larger than prior individuation-focused studies in pediatric (n = 4 [64]) and adult CP (n = 9 [63]), may limit the generalizability of our findings. However, the inclusion of a tightly controlled comparison group of typically developing children whose physical characteristics did not differ from age- and sex-based population norms in the current study increases confidence in the study findings. The absence of neurophysiological or neuroimaging data in the current study precludes insights into neural substrates of individuation abilities. Future work may consider incorporate neuroimaging and neurophysiological methods such as mobile functional neuroimaging via functional near-infrared spectroscopy [105], sensory-motor tractography, or transcranial magnetic stimulation-based assessment of CST integrity [106] to explore neural correlates of impaired finger individuation. While our cross-sectional study design provides valuable insights into motor control, longitudinal studies are needed to delineate developmental trajectories, establish stability, and confirm responsiveness of individuation metrics to changes following intervention. Additionally, though all participants successfully completed the individuation task, attentional differences may have influenced performance in children with CP. While the protocol included audiovisual cues and performance feedback, attentional capacity was not formally assessed, and the single-trial design prevented sensitivity analyses to identify potential bad trials. However, our data preprocessing procedure excluded any trial in which forces did not exceed a minimum force threshold (0.02 N). We also included an iteratively reweighted robust least squares linear regression function (*robustfit*, MATLAB) that accounts for potential outlier data points when computing the Individuation Index. Data inspection also revealed no Individuation Index values exceeding ± 3 SD of the respective group means for overall or

force direction–specific measures. Additionally, participants with CP also successfully completed the PPT, a task requiring sustained cognitive engagement [107], supporting our contention that motor control impairments, rather than attentional deficits, were the primary contributors to their individuation deficits. Further, time restraints and concerns of fatigue restricted bilateral individuation evaluations to only 6 children with CP. Despite this small sample, preliminary sub-group analyses revealed hand- and finger-specific differences in individuation ability, which aligns with preliminary prior research in children with CP [64] and reinforces the need to assess both hands even in children displaying unilateral impairment [108]. Similar practical constraints also precluded the assessments of all fingers, with the choice of tested fingers driven by the distinct functional roles of the thumb, index, and ring finger in common daily activities (i.e., screen tapping, typing, and grasping function, respectively). While prior work in children with hemiparetic CP [64] and adults post-stroke [48, 70] suggests individuation deficits are the greatest in the ring finger and the least in the thumb, supporting our decision to prioritize evaluation of these fingers, future work should attempt to capture finger enslavement patterns across all fingers. Finally, including children with more severe impairments (i.e., MACS levels III-V) and different CP subtypes (e.g., dyskinetic or ataxic CP) would enhance the clinical relevance and generalizability of these findings.

Conclusion

This study demonstrates that children with CP exhibit significant impairments in finger individuation that are finger- and force direction-specific, with these fine-grained metrics distinct from composite functional metrics provided by common clinical assessments. These findings support the HAND protocol as a valid, reliable, and sensitive method for quantifying nuanced finger individuation deficits across digits and directions in children with CP. Finger individuation assessments can provide critical insights into the intricate control mechanisms underlying dexterous function, and hold significant potential to inform the design of targeted rehabilitation strategies to improve hand use after developmental brain injury.

Abbreviations

BBT	Box and Blocks Test
BMI	Body mass index
Con	Typically developing control children
CP	Cerebral palsy
CST	Corticospinal tract
FDT	Functional Dexterity Test
GMFCS	Gross Motor Function Classification System
HAND	Hand Articulation Neuro-training Device
LMM	Linear mixed-effect model
MACS	Manual Ability Classification System
meanDevP	Mean deviation from baseline fingertip forces
PPT	Purdue Pegboard Test
SMC	Selective motor control

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Supplementary Material 4.

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Author contributions

JX, CMM, and OAK conceived the study design. CMM, SVWW, and GC recruited study participants. DR, OAK, DYH, and BC collected individuation data, and OAK conducted upper limb clinical assessments. DR and BC processed individuation data under the supervision of JX. OAK, DR, BC, and JX performed data analyses. OAK and BC wrote the main manuscript text. OAK, BC, and JX created figures. OAK created tables with input from JX and CMM. Manuscript revisions were done by OAK, CMM, and JX. All authors read and approved the final version of the manuscript.

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Data availability

Data used and/or analyzed for the current study will be made available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Written informed consent was obtained from parents or caregivers, and verbal assent was obtained from all participants before data were collected. All procedures were approved by the Institutional Research Board at the University of Georgia.

Consent for publication

Written consent for use of personal data in the form of image(s) for publication was obtained from participant's parent or legal guardian.

Competing interests

The authors declare no competing interests.

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