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Exploring the Feasibility of Estimating Grip Aperture in Children Using Smartphone Video-Based Hand Tracking: A Preliminary Study

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Highlights

What are the main findings?

- Maximum grip aperture increased with object size in both groups, but group differences in mean values were not statistically significant.
- Between-child variability decreased for larger blocks in typically developing children but remained relatively high in children with developmental delay, with an exploratory between-group variance difference for the largest block.

What are the implications of the main findings?

- Single-smartphone video-based hand tracking may enable quantification of object-size-related changes in grip aperture and between-child differences under the studied conditions.
- Individual grip aperture adjustment and the accuracy, reliability, and clinical utility of the measurement need further validation in larger, age-matched samples and against a reference measurement system.

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Abstract

Background/Objectives: This study examined whether maximum grip aperture (MGA) estimated from smartphone video scales with object size, compared typically developing (TD) children and children with developmental delay (DD), and explored its association with modified Box and Block Test (mBBT) completion time. **Methods:** Twenty-four children (10 TD, 14 DD) were instructed to transfer blocks (1.5, 2.5, 5 cm). MediaPipe-tracked MGA (maximum thumb–index distance before block contact) was normalized to hand size. Twenty children (8 TD, 12 DD) with valid trials in all sizes were analyzed with a mixed-design ANOVA. **Results:** Analyzable measurements were obtained from 566 of 581 task attempts (97.4%). Normalized MGA increased with block size ($F(2, 36) = 29.66$, $p < 0.001$, partial $\eta^2 = 0.622$); group ($p = 0.295$) and interaction ($p = 0.421$) effects were not significant. Between-child SDs decreased with block size in the TD group (0.25, 0.22, 0.17) but remained high in the DD group (0.37, 0.35, 0.40), with an exploratory large-block variance difference (unadjusted $p = 0.017$). **Conclusions:** Single-smartphone hand tracking

showed preliminary feasibility for quantifying object-size-related changes in grip aperture under the studied conditions. Between-child variability suggests examining individual grip aperture adjustment alongside group means; accuracy, reliability, and clinical utility require further validation.

Keywords: developmental delay; maximum grip aperture; markerless hand tracking technology; preliminary study

1. Introduction

Developmental delay (DD), a delay in attaining age-expected milestones in motor, language, cognitive, social, or adaptive domains, can affect children's daily functioning; early identification and referral are therefore important [1–3]. Because early childhood is a period of high neuroplasticity, early intervention can broaden developmental opportunities [4]. In Korea, early intervention needs [5] and screening methods [6,7], including the Korean Developmental Screening Test for Infants and Children (K-DST) [8], have been studied; screening identifies children who need further evaluation, and diagnosis follows a comprehensive developmental evaluation [1].

Caregiver-report tools such as the K-DST ask whether a child can perform age-expected skills [8] but do not show how the hand moves during a task. In reach-to-grasp movements, the fingers open during hand transport and grip aperture peaks before contact, at about two-thirds of the movement time [9]; kinematic studies have quantified this maximum grip aperture (MGA) and its scaling to object size in children [10–12].

MGA, the largest thumb–index distance during reaching, increases systematically with object size [9,10]. This anticipatory grip scaling reflects movement planning based on visually perceived object properties [10].

Early motor differences can be subtle and difficult to detect through brief observation, and quantitative assessment of grasping may reveal differences in fine motor control that are not apparent from observation or questionnaires. Grasp control continues to develop through childhood: younger children open their hands wider, leaving a larger safety margin [12]; reaching becomes smoother and less variable with age [13]; and the grasp must be planned from perceived object properties and previous reaching accuracy [14]. Impaired predictive motor control has been proposed as a core deficit in developmental coordination disorder [15], differences in reach-to-grasp planning and execution have been reviewed in autism spectrum disorder (ASD) [16], and children with ASD showed a larger MGA when visual feedback was available [11]. Because reach-to-grasp control can thus vary with development and developmental characteristics, individual children's grip aperture adjustment should be examined alongside group means.

MGA has traditionally been measured with three-dimensional motion analysis or with markers and sensors attached to the fingers [11]. These systems are precise but require costly equipment and a laboratory, and attaching markers may itself be difficult for children with DD.

Markerless hand tracking reduces these constraints: MediaPipe estimates 21 hand landmarks in every frame of ordinary RGB video [17]. Three-dimensional approaches using a depth camera [18] or multiple RGB cameras in adults [19] and children [20] have been compared with reference systems but require additional hardware. Single-camera measurements have been compared with touchscreen [21], accelerometer [22], and three-dimensional gait [23] references, although their spatial accuracy is lower than that of a depth-enhanced approach [18] and depends on the relative position of the camera and the participant [23]. A single smartphone requires no depth sensor, multi-camera calibration,

or worn equipment and can therefore be used in therapy rooms and kindergartens; for example, it has been used to classify grasp types in children with cerebral palsy [24]. Building on these advances, pre-contact changes in grip aperture with object size, and their variability between children, need to be quantified from single-smartphone video in children with DD.

This study therefore aimed (1) to determine whether pre-contact MGA scaling to object size can be quantified in young children from single-smartphone video with MediaPipe-based hand tracking in a clinical setting, (2) to compare MGA and its between-child variability between typically developing (TD) children and children with DD at a preliminary level, and (3) to explore the association between MGA-related measures and performance on the modified Box and Block Test (mBBT). The primary aim was to establish the technical feasibility of video-based measurement.

2. Materials and Methods

2.1. Participants

Twenty-four children participated: 10 typically developing (TD) children and 14 children with developmental delay (DD). Recruitment took place from July to October 2025. Children with DD were recruited from hospitals, developmental therapy centers, and a special education kindergarten, whereas TD children were recruited from siblings of children attending these facilities and from a general kindergarten. Children aged 18–84 months (in completed months) who could follow simple instructions were eligible; those with restricted upper-limb movement, abnormal muscle tone, or visual or hearing impairment were excluded.

The DD group comprised children receiving rehabilitation therapy because of a diagnosed developmental disability or developmental concerns identified by a physician or therapist, as reported in caregiver interviews and reviewed with the responsible therapist. Six had a confirmed diagnosis (ASD, n = 2; global developmental delay, n = 2; language developmental delay, n = 1; spastic cerebral palsy, n = 1), and eight were receiving speech therapy (n = 7) and/or sensory integration therapy (n = 4) without a formal diagnosis, two of whom had possible attention-deficit/hyperactivity disorder. For the child with spastic cerebral palsy, the responsible therapist judged that the condition would not interfere with task performance. TD children had no developmental concern or history of related therapy.

Caregivers completed the K-DST [8], which was used only to describe the participants (Table 1); for the 9 children older than 71 months, assessed with the 66–71-month form, the results were descriptive only. Caregivers provided written informed consent, and the study was approved by the Institutional Review Board of Dongguk University (DUIRB2025-04-21).

Table 1. Participant composition of the analysis data.

Characteristic	TD	DD
Number of children in the overall analysis (n)	10	14
Mean age in the overall analysis, months (SD)	57.3 (15.3)	68.4 (12.0)
Number of children in the primary analysis (n)	8	12
Mean age in the primary analysis, months (SD)	60.5 (15.6)	67.0 (12.4)
Overall age range, months	43–80	40–83
Age range in the primary analysis, months	43–80	40–83
Overall sex (boys/girls)	5/5	10/4
Children with a confirmed diagnosis (overall/primary)	0/0	6/5
K-DST: further evaluation recommended in at least one domain (n)	2	6

K-DST: follow-up testing required in at least one domain without a recommendation for further evaluation (n)	4	6
K-DST: at or above peer level in all domains (n)	4	2
K-DST fine motor domain below peer level (n)	2	8

Note. K-DST results are provided to describe participants' developmental characteristics and were not used as a criterion for group classification.

The primary analysis included the 20 children (8 TD, 12 DD) with at least one valid trial in each block-size condition. The other 4 children (2 TD, 2 DD) had no valid trials in one (n = 3) or two (n = 1) conditions and were excluded from the primary analysis. Exclusion depended on whether valid trials were obtained, not on MGA values, and the valid trials of the excluded children were included in a trial-level analysis of all 24 children; nevertheless, selection bias in the primary sample cannot be ruled out. The sensitivity analysis included the 17 children (6 TD, 11 DD) with at least five valid trials in each condition.

2.2. Assessment Setting and Block Task

2.2.1. Experimental Setup

Assessments took place in a quiet room at the participating hospitals, developmental therapy centers, and kindergartens, with a desk and chair suited to the child and a footrest when needed. The hand starting position, the block starting position (15 cm from the hand starting position), and a wooden target box (40 cm from the block starting position) were marked on the desk (Figure 1a). Videos were recorded with the rear camera of an iPhone 12 Pro (Apple Inc., Cupertino, CA, USA) placed 70 cm from the end of the wooden box and 20 cm above the desk, with the child in the center of the frame (Figure 1b).

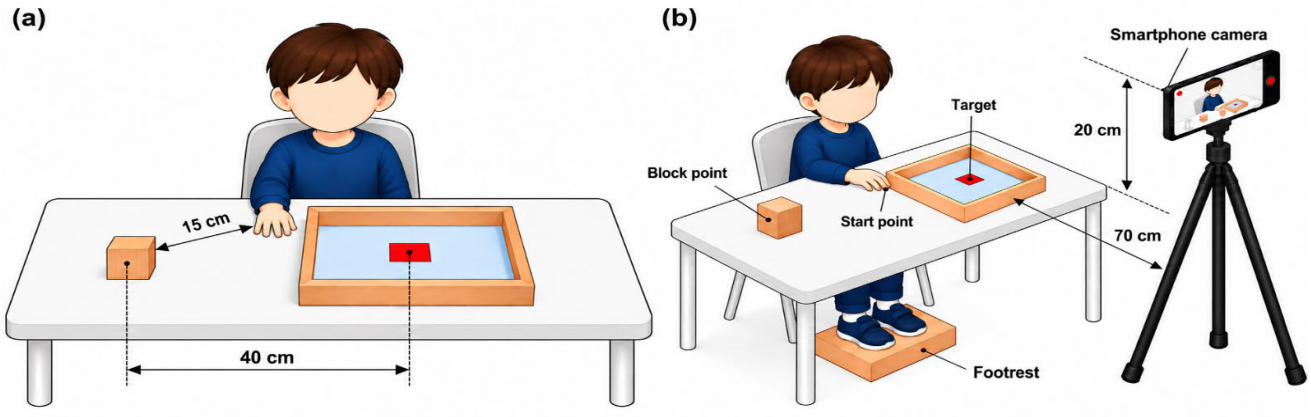


Figure 1. Experimental task configuration and video recording setup. (**a**) Spatial layout of the task: 15 cm from the hand starting point to the block position and 40 cm from the block position to the target. (**b**) Seated posture of the child using a footrest and the smartphone camera fixed on a tripod; the camera was placed 70 cm from the end of the wooden box and 20 cm above the desk. The block in the figure is illustrative; three sizes (1.5, 2.5, and 5 cm) were actually used.

2.2.2. Instructions

All children were right-handed, as identified from caregiver report and by observing the hand used to write their name or to reach for a presented object. The child sat with the left hand under the desk and the right hand at the starting position and, on the evaluator's verbal instruction ("start"), grasped the block and transferred it to the target box.

2.2.3. Procedure

Small (S, 1.5 cm), medium (M, 2.5 cm), and large (L, 5 cm) blocks were used, with the order of size conditions randomized for each child. Ten trials were planned for each size, and consecutive transfers of the same block were recorded. Additional trials were allowed when a planned trial could not be used because of evaluator intervention or task performance before recording began, and trials that the child spontaneously continued after the planned 10 were also recorded. The same inclusion criteria were applied to all recorded trials, and trials in which the child did not complete the prescribed procedure (e.g., starting before the instruction, switching to play, or wishing to stop) were excluded. The number of valid trials per child and size condition therefore differed from the planned 10.

2.3. Video Processing and Quality Review

2.3.1. Video Recording and Hand Tracking

Videos were 1920 × 1080 pixels, and the frame rate, checked for each file, was 30 or approximately 59.9 frames per second (fps). Hand landmarks were extracted with the HandLandmarker task of MediaPipe (version 1.0.0; Google LLC, Mountain View, CA, USA), and the blocks, starting-position markers, and target box were detected with a YOLOv8n model trained by the research team. Normalized MediaPipe coordinates were converted to pixel coordinates using the frame width and height, and hand landmarks and object detections were synchronized by frame number.

MediaPipe was run in video mode for up to two hands per frame, with minimum confidence values of 0.7, 0.5, and 0.5 for hand detection, hand presence, and tracking. When two hands were detected in the same frame, the smaller hand was taken as the child's, on the assumption that the adult evaluator's hand appears larger. Frames with a single detected hand were not excluded automatically, and correct tracking of the child's hand was checked during subsequent video review.

2.3.2. Object Detection

The YOLOv8n model (Ultralytics version 8.3.229; Ultralytics Inc., Frederick, MD, USA; pretrained on COCO) was fine-tuned for 100 epochs (input size 640 px, batch size 16) to detect the block, the two starting markers, and the target box, using 2034 frames from 34 videos (1568 frames from 7 participating children and 466 frames from 5 children not in the analysis sample) labeled by the first author in Roboflow (Roboflow Inc., Des Moines, IA, USA; https://roboflow.com, accessed on 20 November 2025), augmented to 6102 images by random 90° rotation and brightness and exposure changes; detections with a confidence of 0.20 or higher were used. In child-level 3-fold cross-validation on the non-augmented frames of children not used for training, the mean mAP50 was 0.89 (range 0.82–0.99), precision 0.89 (0.75–0.98), and recall 0.85 (0.76–0.97); block mAP50 was 0.87–0.99, whereas recall for the hand starting marker was 0.49 and 0.53 in two folds. These metrics concern object detection only. The detections were used only to segment trials and estimate first contact; grip aperture was calculated from MediaPipe landmarks alone.

2.3.3. Measurement Interval and Video Review

Each trial was the unit of measurement, and its interval ran from the onset of hand movement toward the block to immediately before the first hand–block contact. Onset was detected automatically as the end of the last period of wrist stationarity of at least 0.3 s before block displacement; if none was found, a provisional onset 3 s before displacement was set and the trial was reviewed further, and when the hand did not start at rest on the desk, onset was the time it left the desk. First contact was estimated from the first displacement of the block and confirmed in the original video. Boundaries were corrected

when movement preceded the detected onset, contact preceded the estimated time, or evaluator movement entered the interval.

All video review and boundary correction were performed by the first author, an occupational therapist with 6 years of research experience, who was aware of participants' group membership. For all candidate trials, the generative artificial intelligence tool Claude (Sonnet 5 and 5.5; Anthropic, San Francisco, CA, USA) was used as an auxiliary check of whether each candidate was an actual task trial and had been detected appropriately. Trials flagged as uncertain by Claude were re-examined in the original video by the first author, who made all final inclusion decisions.

The review checked movement onset, first contact, right-hand use, evaluator intervention, landmark tracking quality, duplicate detection of the same approach, and missing coordinates; uncertain trials were examined frame by frame. Trials were included only when the child approached the block independently with the right hand, onset and first contact could be identified, the child's hand landmarks were tracked at an analyzable level during the interval, and the same approach was not detected more than once (Table 2).

Table 2. Reasons for excluding candidates from the analysis.

Reason	Number of Candidates (n)
Evaluator movement or physical assistance	33
Suspected use of the non-dominant hand	2
Automatically detected candidates not confirmed as an actual approach or contact by the child	4
Duplicate detection of the same approach–grasp event	7
Approach or first-contact boundary not determined	10
Uncertain measurement quality	3
Total excluded	59

Note. Values are based on candidate records, not actual task attempts. Candidates placed on hold were also excluded from the analysis.

2.3.4. Interpolation and Smoothing

Interpolation and smoothing used only frames before the first contact, and the MGA peak was searched for only within the final measurement interval. Missing landmark coordinates were linearly interpolated (pandas) only when observed values existed on both sides of the gap, for up to 10 frames; longer gaps and gaps at the end of the interval were not interpolated. Because this limit was set in frames, it corresponded to approximately 0.33 s at 30 fps and 0.17 s at 59.9 fps, and a time-based limit is preferable in future studies. Of the 566 analyzed trials, 312 were recorded at 30 fps, and 45 of the 49 peaks that relied on interpolated coordinates occurred in these videos. The analyses were therefore repeated after excluding these peaks and, separately, with the limit standardized to approximately 0.17 s (5 frames at 30 fps and 10 frames at 59.9 fps), recalculating the normalized MGA of affected trials under the new limit as the maximum within the original measurement interval.

Smoothing used a centered moving median filter of approximately 0.17 s (5 frames at 30 fps and 11 frames at 59.9 fps; rounded to the nearest odd number of frames), applied first to the hand-size denominator and then to the normalized ratio; the thumb–index distance was not smoothed separately. Missing values were ignored within the window, so a smoothed value could be obtained for a frame with missing coordinates; such frames could also be selected as the MGA peak. These peaks were flagged as interpolation-dependent peaks and examined in a separate sensitivity analysis (Table 3). The smoothing window did not include frames after first contact.

Table 3. Number of analyzed trials by group and block size.

(**A**) All 24 children

Group (n)	Size	All Trials	Trials with Detected Peaks	Trials with Interpolated Peaks
TD (10)	S	73	68	5
	M	75	69	6
	L	61	60	1
DD (14)	S	126	114	12
	M	116	103	13
	L	115	103	12
Total (24)	-	566	517	49

(**B**) Primary analysis and mBBT analysis sample, 20 children

Group (n)	Size	All Trials	Trials with Detected Peaks	Trials with Interpolated Peaks
TD (8)	S	63	58	5
	M	63	58	5
	L	54	53	1
DD (12)	S	116	104	12
	M	104	91	13
	L	105	93	12
Total (20)	-	505	457	48

Note. TD, typically developing; DD, developmental delay; n, number of children with at least one valid trial. S = 1.5 cm; M = 2.5 cm; L = 5 cm. Trials with detected peaks: hand landmarks detected at the MGA frame; Trials with interpolated peaks: landmarks missing at that frame, so the peak relied on interpolated and/or smoothed values.

2.4. Definition of Normalized MGA and Relative Hand Opening

2.4.1. Normalized MGA

At frame t, grip aperture a(t) was the two-dimensional pixel distance between the thumb and index fingertips. It was normalized by the larger of two hand-size segments, the wrist–middle finger metacarpophalangeal (MCP) joint distance h1(t) and the index–little finger MCP joint distance h2(t):

$$r(t) = a(t)/\max[h1(t), h2(t)]$$

The normalized MGA of each trial, a unitless ratio, was the maximum of the smoothed r(t) from approach onset to immediately before first contact.

Measuring aperture and hand size in the same frame partly compensates for differences in camera distance. Because h1 shortens in the image mainly when the hand tilts toward the camera and h2 mainly with forearm pronation or supination, taking the larger segment reduces the underestimation of hand size. Both segments can shorten together, however, and such changes need not affect the aperture equally, so this method cannot fully correct for hand position and orientation; its accuracy was not validated against manual or three-dimensional reference measurements.

2.4.2. Relative Hand Opening

Relative hand opening (relative grip aperture) expresses grip aperture relative to the upper level observed during each child's task. For child i, the normalized MGA values of all valid trials in the three conditions were pooled, their 90th percentile (q_i; linear interpolation) was calculated, and each condition mean was divided by q_i and multiplied by 100 (values above 100% were retained). The 90th percentile rather than the maximum was

used to limit the influence of single extreme values from tracking errors or atypical trials; q_i therefore represents a large aperture observed in this task, not the child's maximum voluntary grip aperture. Because q_i pools trials, it may be less stable when few trials are available and is weighted toward conditions with more trials; it was therefore also recalculated with each trial weighted by the inverse of the number of valid trials in its condition. Relative hand opening is derived from normalized MGA and is not an independent measurement. Overall means gave equal weight to the three conditions, and the size-related increase was the difference between the L and S condition means.

2.5. Definition of mBBT Completion Time

To obtain an index of manual task performance for comparison with grip aperture, the mBBT was administered following previous studies [25,26]. One therapist measured from the video the time from the hand's first touch of the first block to the placement of the 16th block, to avoid the influence of reaction time to the verbal start instruction in young children. Because this interval differs from those of previous studies [25,26], completion times were not compared with normative data and were used only as a within-sample index of task speed. Each child's mean time across completed trials was used (19 of the 20 children completed 3 trials and 1 completed 2). Inter-rater reliability was not assessed.

2.6. Statistical Analysis

The primary analysis used each child's condition-wise mean normalized MGA (the arithmetic mean of 4–15 valid trials per condition), giving equal weight to each of the 20 children regardless of the number of trials.

A 2 (group) × 3 (block size) mixed-design analysis of variance (ANOVA) was performed, with Mauchly's test of sphericity (Greenhouse–Geisser correction when violated), the Shapiro–Wilk test of residuals, the Brown–Forsythe (median-centered Levene's) test of homogeneity of variance, and partial η^2 as the effect size; relative hand opening was analyzed in the same way. Group differences (TD − DD) were reported with Welch-type 95% confidence intervals (CIs) and Hedges' g. With 8 TD and 12 DD children, only a large effect (Cohen's d ≈ 1.35; two-sided $\alpha = 0.05$, 80% power) could be detected, and nonsignificant results were interpreted accordingly.

A linear mixed-effects model (LMM) with age, group, block size, and group × size as fixed effects and a random intercept for each child (reference categories: DD and L) was fitted to the 566 valid trials of all 24 children; this trial-level model accounts for repeated trials within children and age differences between groups and uses all participants. Holm correction was applied to 9 contrasts (group differences in each size condition and size differences within each group) and separately to 3 exploratory contrasts comparing size-related increases. Sensitivity analyses excluded interpolated-peak trials, restricted the sample to the 17 children with at least 5 valid trials per condition, and repeated the primary analysis with smoothing windows of 0.10, 0.17, 0.25, and 0.33 s, recalculated from the stored landmarks using only frames within each original interval and taking the maximum rather than the value at the reviewed peak frame.

Associations between mean mBBT completion time and six MGA-related indices were explored in the 20 children using Spearman correlation and rank-based partial correlation adjusted for age or for age and group (the correlation of the residuals after regressing the ranks of each variable on the covariates). Holm correction was applied to the six correlations within each model, and 95% CIs were calculated with Fisher's z transformation and degrees of freedom adjusted for the covariates. Robustness was examined by restricting the sample to children who completed three mBBT trials, excluding interpolated-peak trials, conducting a leave-one-out analysis, and using the shortest instead of

the mean completion time. Analyses were performed with the pingouin (version 0.6.1) and statsmodels (version 0.14.6) packages in Python (version 3.12.3; Python Software Foundation, Wilmington, DE, USA) ($\alpha = 0.05$).

3. Results

3.1. Participants and Analysis Data

Of the 24 children analyzed (10 TD, 14 DD), 20 (8 TD, 12 DD) were included in the primary analysis. Mean age was 57.3 months (SD 15.3) in the TD group and 68.4 months (SD 12.0) in the DD group overall and 60.5 (SD 15.6) and 67.0 months (SD 12.4) in the primary analysis sample; age ranged from 43 to 80 months (TD) and from 40 to 83 months (DD) in both samples. The sex distribution (overall: TD, 5 boys and 5 girls; DD, 10 boys and 4 girls; primary sample: 3/5 and 8/4) did not differ between groups (Fisher's exact test, $p = 0.40$ and $p = 0.36$). Six DD children overall and 5 in the primary sample had a confirmed diagnosis (Table 1).

Of 625 candidate records (591 detected automatically and 34 added during video review), 59 were excluded (Table 2), and 566 (90.6%) yielded analyzable measurements. Because candidates also included evaluator movements, detection noise, and duplicate detections, they were distinguished from task attempts. After excluding the 44 candidates that were not task attempts by the child (evaluator movements, 33, including 25 of the 34 added candidates; detection noise, 4; duplicate detections, 7), 581 task attempts remained, of which 566 (97.4%) were measured. Only one added candidate was included in the analysis.

The final data comprised 566 valid trials from 24 children, with landmarks detected at the peak frame in 517 trials and interpolated peaks in 49 (Table 3A). The primary and mBBT analyses used 505 trials from the 20 children (457 detected and 48 interpolated peaks; Table 3B), and the analyses excluding interpolated peaks used 517 and 457 trials, respectively.

3.2. Normalized MGA and Relative Hand Opening by Size and Developmental Group

Group means of normalized MGA and relative hand opening increased in the order S < M < L in both groups (Table 4, Figure 2). For both measures, the main effect of block size was significant (normalized MGA: $F(2, 36) = 29.66$, $p < 0.001$, partial $\eta^2 = 0.622$; relative hand opening: $F(2, 36) = 30.85$, $p < 0.001$, partial $\eta^2 = 0.632$), whereas neither the main effect of group ($F(1, 18) = 1.16$, $p = 0.295$ and $F(1, 18) = 1.28$, $p = 0.272$) nor the group × size interaction ($F(2, 36) = 0.89$, $p = 0.421$ and $F(2, 36) = 0.55$, $p = 0.582$) was significant (Table 5); sphericity was not violated for normalized MGA (Mauchly's $W = 0.777$, $p = 0.103$). For relative hand opening, the results were similar when q_i gave equal weight to each condition (size, $F(2, 36) = 31.18$, $p < 0.001$; group, $p = 0.316$; interaction, $p = 0.581$). Because relative hand opening is derived from normalized MGA, it is not an independent test of the size effect; it shows that the pattern was maintained when grip aperture was expressed relative to each child's observed upper range.

Group differences (TD − DD) in normalized MGA were 0.06 (95% CI: −0.24 to 0.35; Hedges' $g = 0.17$), 0.13 (95% CI: −0.14 to 0.40; $g = 0.41$), and 0.23 (95% CI: −0.05 to 0.51; $g = 0.65$) in the S, M, and L conditions, and 0.14 (95% CI: −0.10 to 0.38; $g = 0.47$) for the overall mean; all CIs included 0.

Residuals of normalized MGA did not deviate from normality (Shapiro–Wilk $W = 0.988$, $p = 0.842$). In exploratory Brown–Forsythe tests without correction for multiple comparisons, a group difference in between-child variance was observed only for normalized MGA in the L condition ($F(1, 18) = 6.89$, unadjusted $p = 0.017$; Table 4, Figure 2). For normalized MGA, between-child SDs were 0.35–0.40 in the DD group and 0.17–0.25 in the TD

group, and the SD of the L − S increase was 0.37 and 0.21, respectively. Normalized MGA increased in the order S < M < L in 10 of 12 DD children and 6 of 8 TD children.

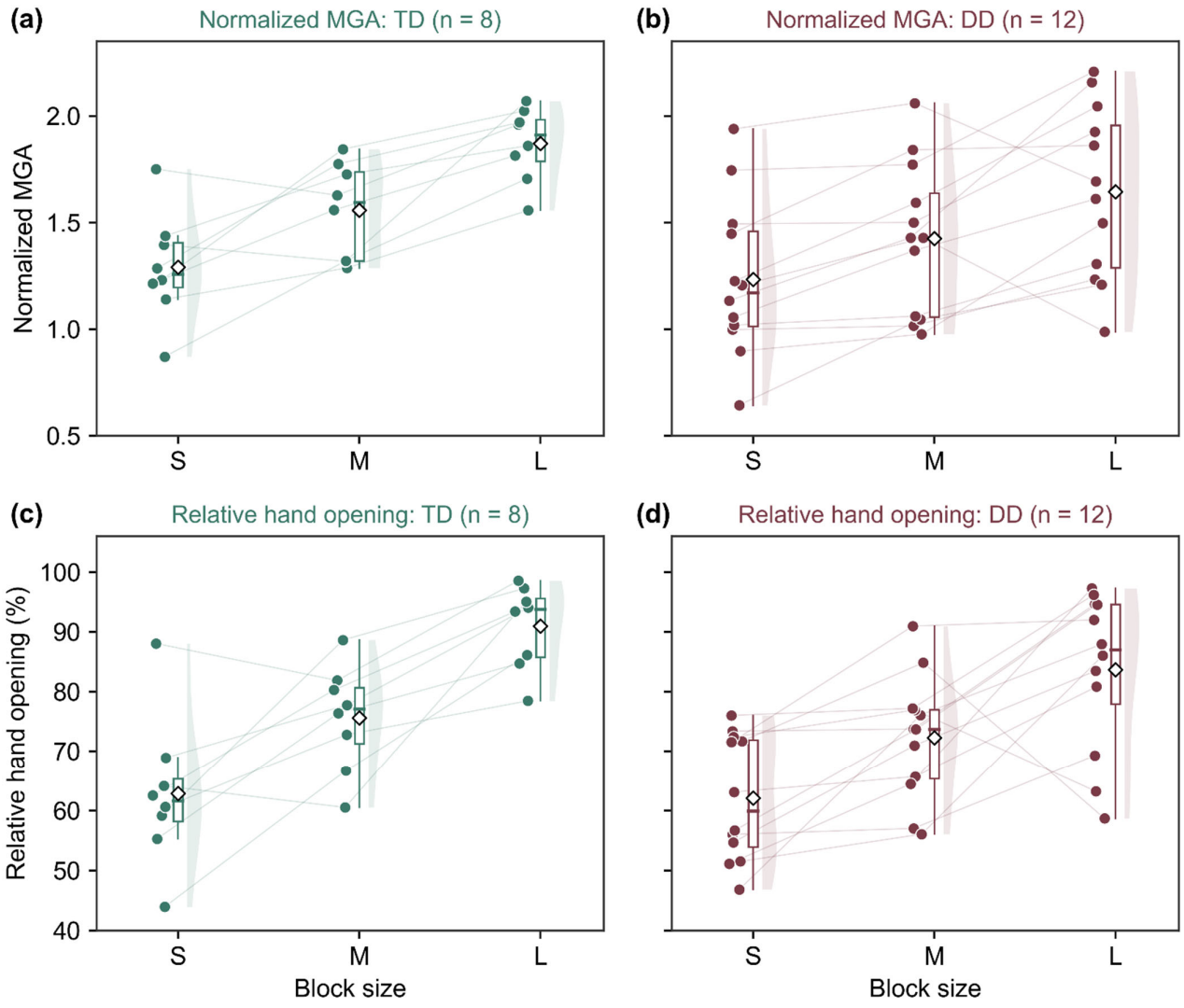


Figure 2. Normalized MGA (**a**,**b**) and relative hand opening based on each child's 90th percentile (**c**,**d**) by block size. Left panels (**a**,**c**) show typically developing children (TD, n = 8), and right panels (**b**,**d**) show children with developmental delay (DD, n = 12). Dots represent individual children, and thin lines connect measurements from the same child across block sizes. Each box shows the interquartile range, the line inside the box shows the median, and whiskers extend to 1.5× the interquartile range; open diamonds represent group means. Half-violin plots show kernel density estimates, which are only approximate with 8 and 12 children; their width does not represent sample size.

Table 4. Normalized MGA and relative hand opening (based on each child's 90th percentile) by group and block size, with group comparison of between-child variance, in the 20 children of the primary analysis.

Measure	Size	TD	DD	Variance ratio	Brown–Forsythe	*p*
		Mean (SD)	Mean (SD)	(DD/TD)	*F*(1, 18)	
Normalized MGA	S	1.29 (0.25)	1.23 (0.37)	2.08	1.03	0.323
	M	1.56 (0.22)	1.42 (0.35)	2.51	1.23	0.282

	L	1.87 (0.17)	1.64 (0.40)	5.46	6.89	0.017
Relative hand opening (%)	S	62.83 (12.58)	62.09 (10.43)	0.69	0.15	0.703
	M	75.62 (8.88)	72.31 (10.33)	1.35	0.15	0.699
	L	90.98 (7.06)	83.69 (13.26)	3.52	1.94	0.180

Note. TD, typically developing children (n = 8); DD, children with developmental delay (n = 12). Variance ratio, ratio of the sample variances (DD/TD). Brown–Forsythe *p* values are not adjusted for multiple comparisons.

Table 5. Mixed-design ANOVA of normalized MGA and relative hand opening.

Measure	Effect	F	df	*p*	Partial η^2
Normalized MGA	Group	1.16	1, 18	0.295	0.061
	Size	29.66	2, 36	<0.001	0.622
	Group × size	0.89	2, 36	0.421	0.047
Relative hand opening	Group	1.28	1, 18	0.272	0.067
	Size	30.85	2, 36	<0.001	0.632
	Group × size	0.55	2, 36	0.582	0.030

3.3. Sensitivity Analysis

All sensitivity analyses led to the same conclusions as the primary analysis: the main effect of block size remained significant, whereas neither the main effect of group nor the group × size interaction was significant. This held for the age-adjusted trial-level LMM (566 trials, 24 children), the analysis excluding interpolated-peak trials, the 17-child subsample (Greenhouse–Geisser corrected), smoothing windows of 0.10–0.33 s ($F(2, 36) = 25.49–42.50$, all $p < 0.001$), and an interpolation limit standardized to approximately 0.17 s, which affected 19 of 505 trials (3.8%), all at 30 fps (normalized MGA: $F(2, 36) = 31.41$, $p < 0.001$; relative hand opening: $F(2, 36) = 33.30$, $p < 0.001$). In the LMM, all size differences within each group remained significant after Holm correction (all $p < 0.001$); the group differences (TD − DD) were 0.04 (95% CI: −0.21 to 0.29), 0.17 (95% CI: −0.08 to 0.42), and 0.20 (95% CI: −0.05 to 0.45) in the S, M, and L conditions; and the increase from S to L (TD, 0.614; DD, 0.449) did not differ significantly between groups (Holm-adjusted $p = 0.150$).

3.4. Exploratory Association with mBBT Completion Time

Mean normalized MGA and mean mBBT completion time were not significantly correlated without adjustment ($\varrho = 0.386$, $p = 0.092$). After adjustment for age and group, a positive association was observed ($r = 0.539$, 95% CI: 0.10–0.80, unadjusted $p = 0.021$), but it did not remain significant after Holm correction for the six indices (adjusted $p = 0.126$; Table 6, Figure 3a). Mean relative hand opening showed no statistically significant association with mBBT completion time ($\varrho = 0.153$, $p = 0.519$; age- and group-adjusted $r = 0.180$, $p = 0.475$; Figure 3b). Within-group correlations were similar in the TD and DD groups for mean normalized MGA ($\varrho = 0.524$, $p = 0.183$, and $\varrho = 0.538$, $p = 0.071$) and smaller for mean relative hand opening ($\varrho = 0.357$, $p = 0.385$, and $\varrho = 0.210$, $p = 0.513$), but none was significant (Figure 3).

Table 6. Exploratory association between mean normalized MGA and mBBT completion time (n = 20).

Adjustment	Correlation Coefficient	*p* Before Correction	Holm-Adjusted *p*
None	$\varrho = 0.386$	0.092	0.441
Age	$r = 0.449$	0.054	0.322
Age·group	$r = 0.539$	0.021	0.126

Using the shortest completion time gave a similar result (r = 0.504, p = 0.033; Holm-adjusted p = 0.199). The correlation remained positive when the sample was restricted to children with three mBBT trials and when interpolated-peak trials were excluded, and leave-one-out coefficients ranged from 0.427 to 0.625 (p before correction, 0.007–0.087).

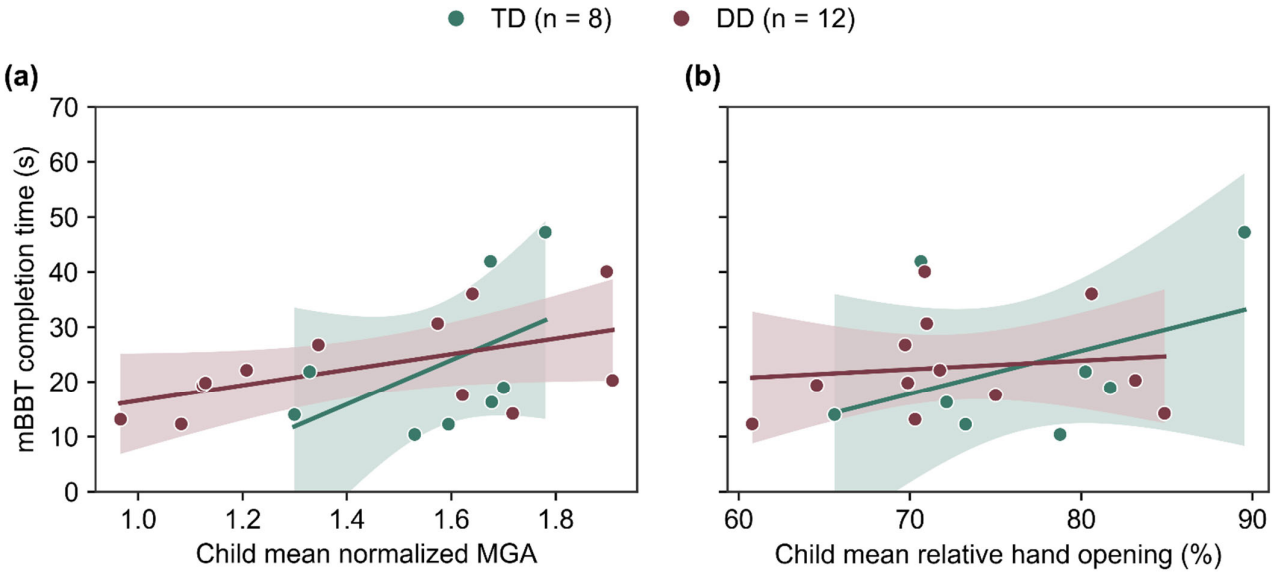


Figure 3. Each child's mean right-hand mBBT completion time plotted against (**a**) mean normalized MGA and (**b**) mean relative hand opening. Each point is an unadjusted observation of one child (8 TD, 12 DD); lines and shaded bands show least-squares regression lines and their 95% confidence bands within each group as a visual summary, whereas the analyses were rank-based.

4. Discussion

Normalized MGA measured from single-smartphone video increased with block size in both groups, and this effect held in all sensitivity analyses. This is consistent with Zoia et al. [10], who found that 5-year-old children scaled grip aperture to object size even with limited visual feedback, and suggests that video-based hand tracking can capture children's grip aperture scaling; it does not, however, establish measurement accuracy or reliability.

Markerless hand tracking has been validated against reference systems mostly in adults or with additional hardware. MediaPipe showed high temporal agreement in clinical hand tasks but lower spatial accuracy than a depth-enhanced approach [18] and has been compared with touchscreen [21] and accelerometer [22] measurements, while grasp kinematics have been reconstructed with multiple RGB cameras [19,20]. The present study extends this work to grip aperture scaling in young children recorded with a single smartphone, but without a reference system, its accuracy cannot be judged.

Grip aperture control depends on task conditions as well as object size; children aged 5–6 years scaled MGA differently with reaching distance and sight of the hand than older children and adults [27]. In this study, both normalized MGA and relative hand opening increased across the three block sizes.

No significant group differences were found, unlike the larger MGA reported in children with ASD under visual feedback [11]; differences in participants, task conditions, and measurement methods may explain this. The absence of significance does not imply equivalence [28]: all CIs included 0, but the effect sizes in the M and L conditions (g = 0.41

and 0.65) mean that group differences cannot be ruled out. The DD group was heterogeneous, including children with ASD, spastic cerebral palsy, and children without a formal diagnosis, and showed greater between-child variability than the TD group; some TD children also scored below peer level in K-DST domains. Subgroups were too small to analyze, and with 20 children statistical power was limited. These results therefore support the preliminary applicability of video-based measurement rather than identifying group differences in grasp control, and future studies should examine individual children's control patterns together with group means.

Between-child variability in normalized MGA decreased with block size in the TD group (SD 0.25, 0.22, and 0.17) but remained relatively high in the DD group (0.37, 0.35, and 0.40); the variance difference for the largest block was an exploratory observation that was not corrected for multiple comparisons (unadjusted $p = 0.017$). Because variability was compared within each block size, it describes differences between children rather than individual changes across sizes. In adults, MGA variability can decrease for larger objects, reflecting safety margins and, near the maximal aperture, biomechanical limits [29–31]. These studies addressed trial-to-trial variability within individuals and cannot be compared directly with the between-child variability examined here, but the possibility that apertures are constrained for larger objects may help interpret the pattern observed in TD children. The relatively high between-child variability in the DD group suggests that grip aperture adjustment to larger objects may differ among children with DD, although variability arising from the measurement process cannot be ruled out. Predictive motor control has been discussed in developmental coordination disorder [32,33], but our clinically heterogeneous DD sample cannot be equated with a DCD cohort, and these data do not demonstrate impaired predictive control. This pattern suggests that group means alone may not adequately describe individual differences in grip aperture adjustment and that video-based measurement could be used to describe individual children's grasp control patterns. Studies with hand-size measurement, three-dimensional reference kinematics, and pre-contact aperture trajectories are needed to test this possibility.

Children with larger mean normalized MGA tended to have longer mBBT completion times. Although the age- and group-adjusted correlation was positive and remained directionally similar in sensitivity analyses, it was not statistically significant after Holm correction (adjusted $p = 0.126$); the confidence interval was also wide (95% CI: 0.10–0.80). Positive but nonsignificant correlations were observed separately in the TD and DD groups, and the present sample does not establish a within-group association or exclude confounding. Mean relative hand opening showed weaker correlations with completion time, but the difference between these associations was not formally established. A larger aperture could reflect an increased safety margin during grasping [12,14], possibly indicating a more cautious grasping strategy in children with less efficient manual control; however, attention, task understanding, grasp configuration, and movement speed could also influence both measures, and the reliability of neither measure was established. Because MGA captures one aspect of the approach phase whereas mBBT completion time combines repeated transport and placement, these exploratory correlations do not establish convergent validity. Future studies should relate pre-contact aperture trajectories to approach time, contact errors, transport time, and independently validated measures of manual function.

Methodologically, this study defined the interval from approach onset to first contact in ordinary RGB video, combined automatic detection with video review to confirm the child's hand and to remove evaluator movements and duplicate detections, and used the larger of two hand-size segments to reduce projection-related shortening. This normalization cannot fully correct for out-of-plane rotation, which can shorten both segments and affect the aperture differently; for perspective changes as the hand approaches the block;

or for occlusion of the thumb or index finger by the palm or block, and these effects may vary with the child and block size. Normalized MGA should therefore be interpreted as an index derived from two-dimensional landmarks rather than as a direct three-dimensional measurement.

This preliminary study has several limitations. First, the number of valid trials differed among children and conditions, some peaks relied on interpolated landmarks, the frame-based interpolation limit concentrated interpolated peaks in 30 fps videos, the video reviewer was aware of group membership, and the reliability of corrected movement boundaries was not assessed. Second, MGA was not compared with three-dimensional motion analysis or another reference measurement, inter-rater agreement for mBBT completion time was not assessed, and relative hand opening is referenced to the observed 90th percentile rather than to maximum grip aperture capacity. Third, the DD group combined children with and without a formal diagnosis, classified by caregiver report and clinical judgment rather than standardized assessment, the K-DST was used outside its normed age range in some children, and the sample was too small for adequate group comparisons or subgroup analyses.

Thus, the results support the preliminary technical feasibility of quantifying young children's grip aperture scaling from single-smartphone video but do not establish accuracy, reliability, clinical validity, or usefulness. Future studies should record video-based MGA simultaneously with three-dimensional motion analysis, assess test–retest and inter-rater reliability, and use larger, well-characterized, age-matched samples to determine whether these indices add information to existing developmental and hand-function assessments.

5. Conclusions

Grip aperture before block contact was quantified from single-smartphone video in young children. Normalized MGA and relative hand opening increased with block size in both groups, consistently across sensitivity analyses, whereas group differences and the MGA–mBBT association were not significant after correction. These findings provide preliminary evidence supporting the technical feasibility of single-smartphone video-based grip aperture measurement under the conditions studied, but they do not establish measurement accuracy, reliability, or clinical validity for developmental assessment. These measurement properties and the potential for clinical application should be validated against a reference system, with reliability assessment, in larger samples with well-defined developmental characteristics.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
DD	Developmental delay
FPS	Frames per second
K-DST	Korean Developmental Screening Test for Infants and Children
mBBT	Modified Box and Block Test
MCP	Metacarpophalangeal
MGA	Maximum grip aperture
RGB	Red, green, blue
RGB-D	Red, green, blue–depth
SD	Standard deviation
TD	Typically developing
ASD	Autism spectrum disorder
CI	Confidence interval

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